Engineering Quality & Durability into Components Using Robust Design

by

Andreas Vlahinos & Ken Kelly

NREL

FreedomCAR

Acknowledgments

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Dr. Subhash Kelkar, Technical Specialist
Durability CAE Methods Dev. Advanced Vehicle Technology
Ford Motor Company

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Director Government Affairs
Plug Power Inc.

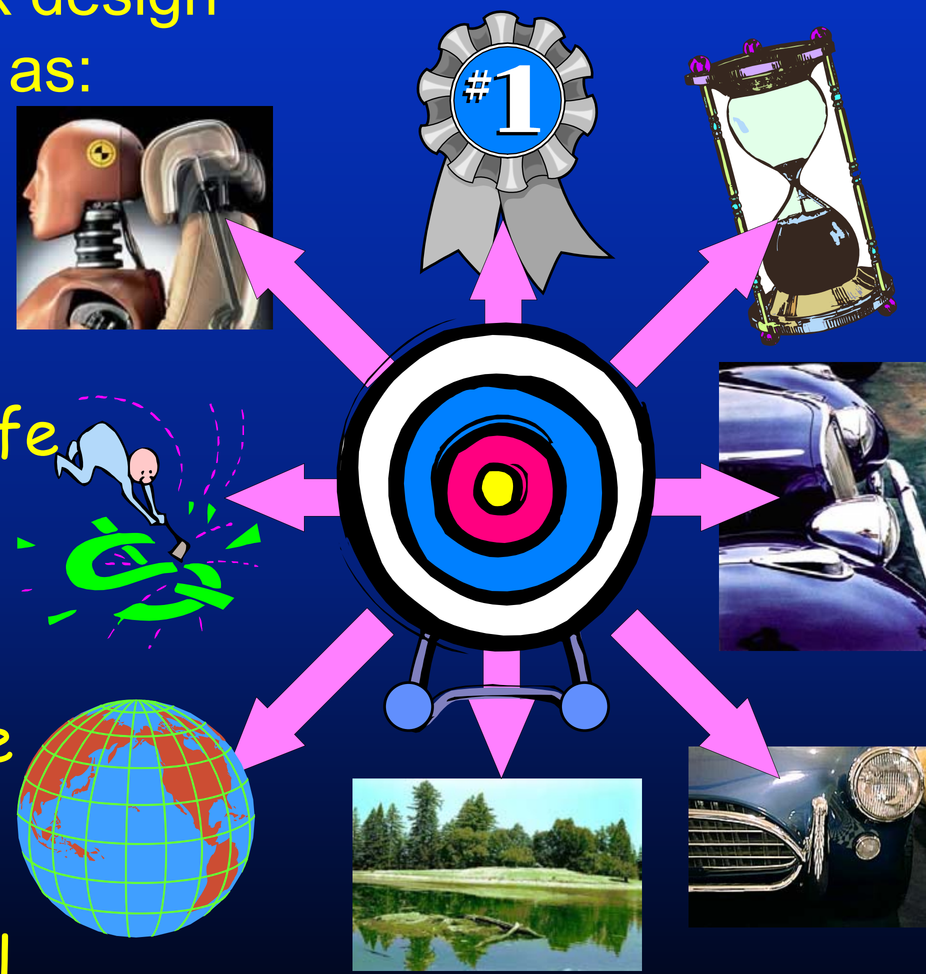
Outline

- Introduction to Engineering Quality
- Program Overview
- Applications:
  - FORD Think Mobility Design Optimization
  - Robust Design of Fuel Cell Stack
  - Power Electronics Cooling with Behavioral Modeling
  - Design For Six-sigma in Battery Thermal Management
  - Design of Experiments Techniques for Road Load Reduction
  - Catalytic Converter
  - Topology Optimization of Fuel Cell Endplates

Contradicting Design Requirements

The need for innovative tools is apparent now more than ever as more complex design requirements are surfacing such as:

- Cost
- Performance & safety
- Quality
- Time to market & short life cycle
- Environmental impacts
- Aesthetics (wow, lust for the product, I got to have it ...)
- Major Changes in Industry's Business Model



Quality - Robust Design

- **Definition** of **Robust Design**:
  Deliver customer expectations at profitable cost regardless of:
  - customer usage
  - variation in manufacturing
  - variation in supplier
  - variation in distribution, delivery & installation
  - degradation over product life

- **Goals** of Robust Design (shift and squeeze)
  - Shift performance mean to the target value
  - Reduce product's performance variability

Statistical Design Performance Simulation?

“ You ‘ve got to be passionate lunatics about the quality issue …”

Jack Welch

“U.S. autos fight poor quality reputation …”

Joe Miller / The Detroit News

“ Product quality requires managerial, technological and statistical concepts throughout all the major functions of the organization …”

Josheph M. Juran

Variation (thickness, properties, surface finish, loads, etc.) is … *THE ENEMY*

DOE, Six Sigma, Statistical FEA, Behavioral Modeling … *THE DEFENCE*

Improved Quality reduced Total Cost

Cost of Defect or Failure

- Lost Customers
- Liability (R&D)
- Recalls (production)
- Rework

Examples:

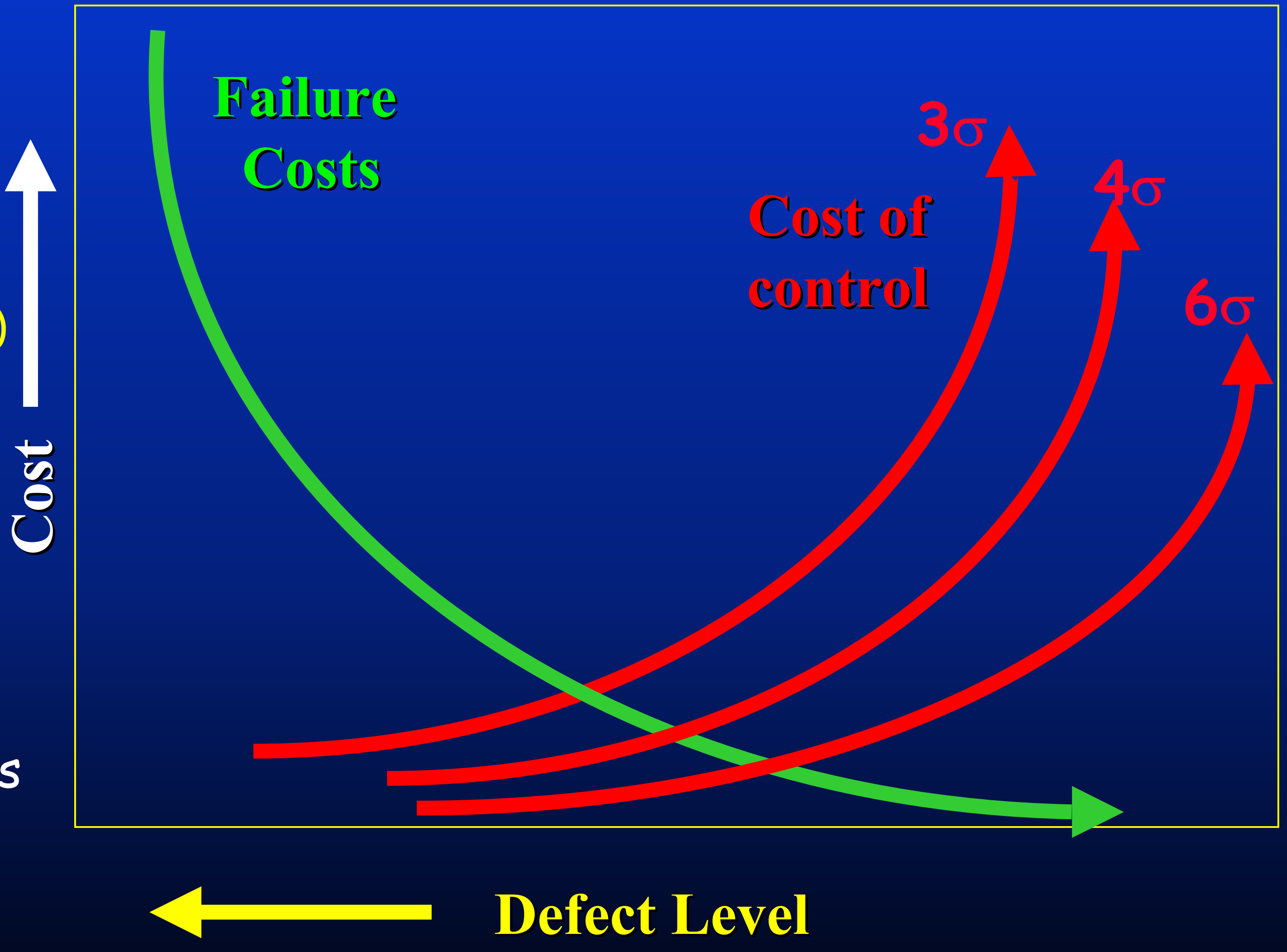
Titanic

Asbestos

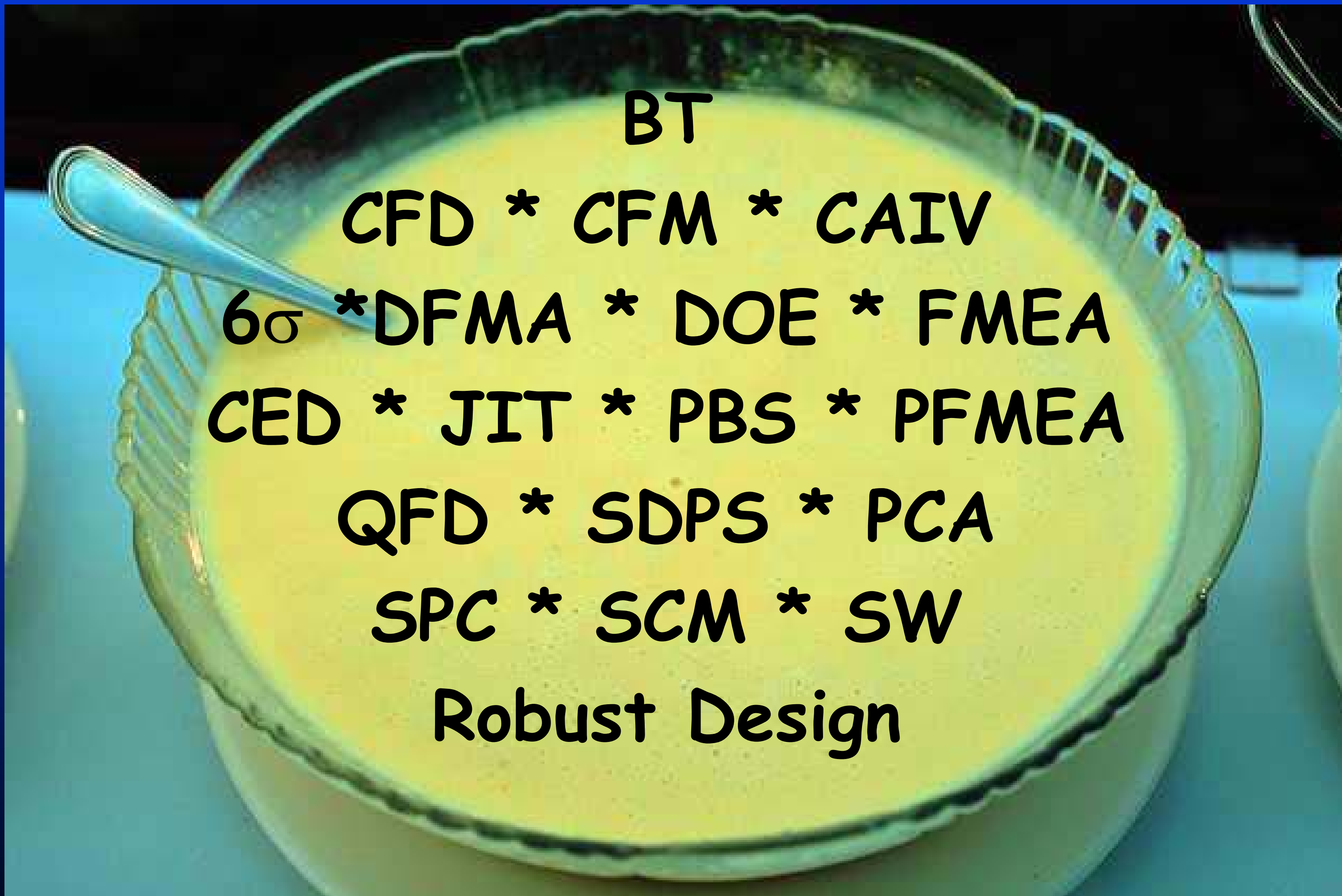
Breast Implants

Bhopal, India

...



Elements of Quality Process: The alphabet soup

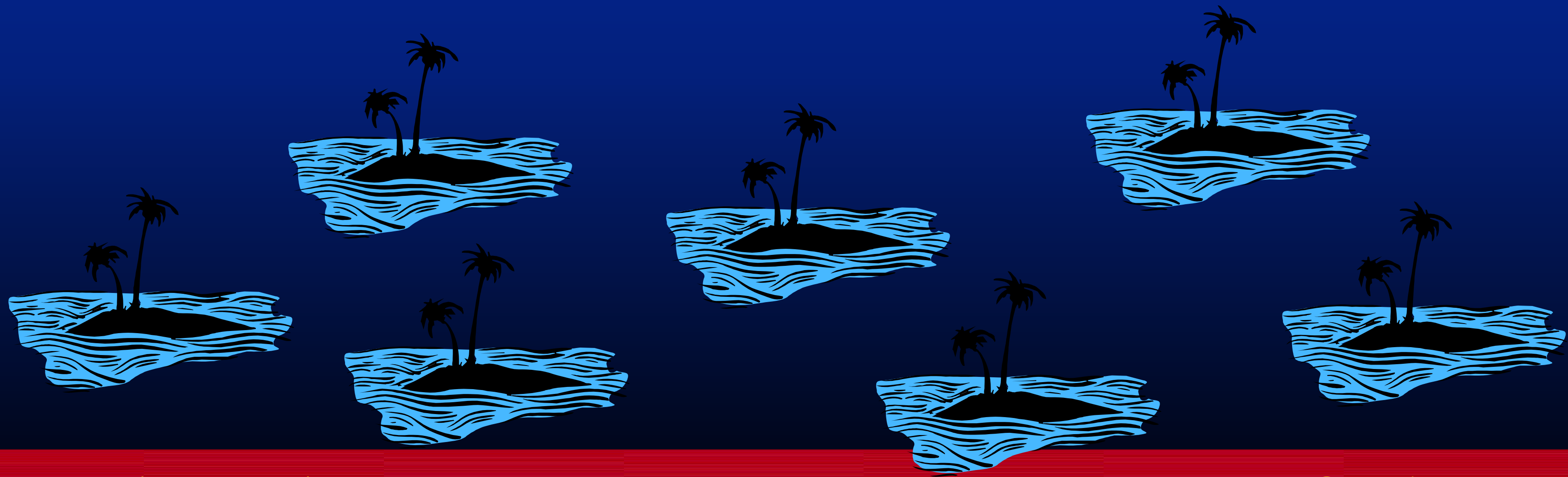


Elements of Quality Management Process

- Agile Improvement Process
- Axiomatic Design *
- Benchmarking & Bench-trending
- Catch-ball
- Cellular Manufacturing
- Continuous Flow Development
- Continuous Flow Manufacturing
- Cycle Time Management
- Defect Reduction
- Design for Manufacturing and Assembly
- Design of Experiments
- Failure Modes effects Analysis
- Cause and Effect Diagrams
- Just In Time
- Performance Based Specifications Process
- Failure Mode Effects Analysis
- Quality Function Deployment
- Robust Design
- Self-Directed Work Teams
- Statistical Design Performance Simulation
- Process Capability Analysis
- Statistical Process Control
- Supply Chain Management
- Synchronous Workshops
- Theory of Constraints *
- Thinking Process Reality Trees
- Total Productive Maintenance

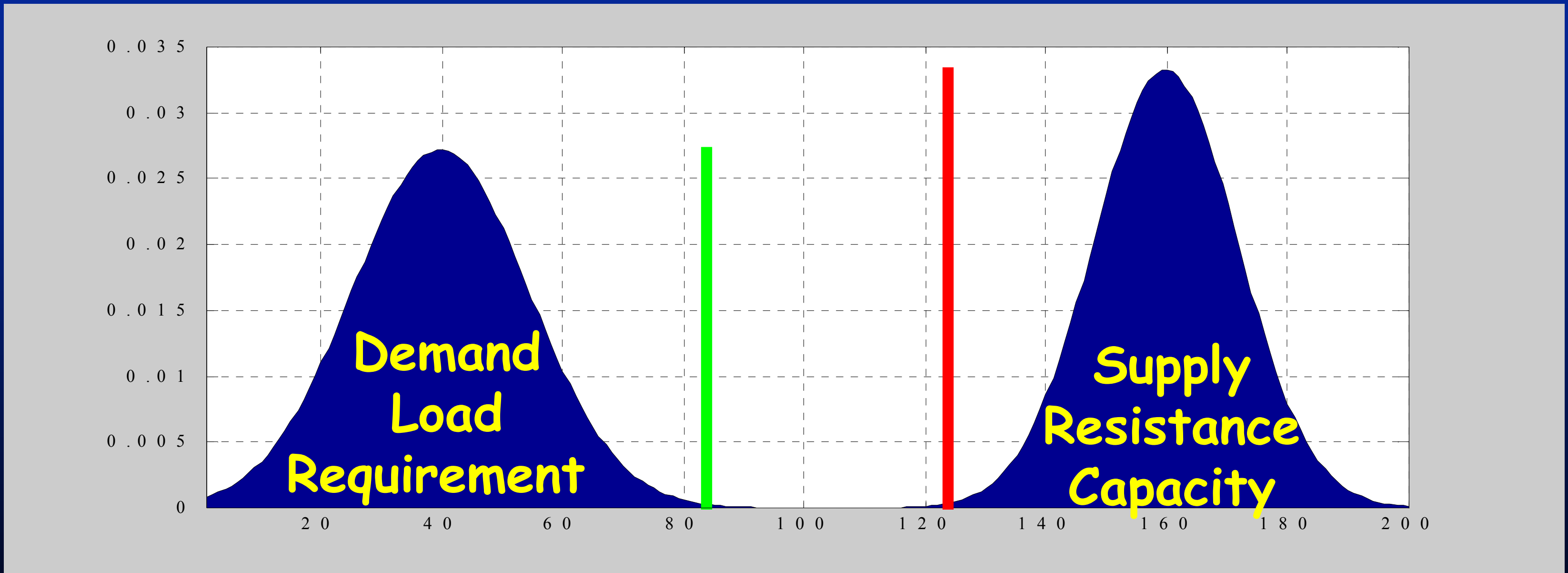
Elements of Quality Management Process

- Although all the elements of quality management process are closely connected they remain apart because they have been developed independently from each other
- Integration of these tools is critical to the organization and necessary for successful federation and robust optimization efforts



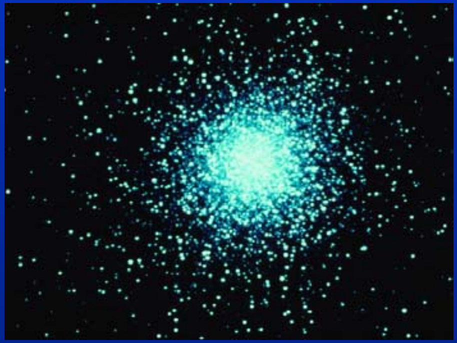
Traditional Deterministic Approach

- Accounts for uncertainties through the use of empirical Safety factors:
  - Are derived based on past experience
  - Do not guarantee safety or satisfactory performance
  - Do not provide sufficient information to achieve optimal use of available resources



Noise & Control Parameters

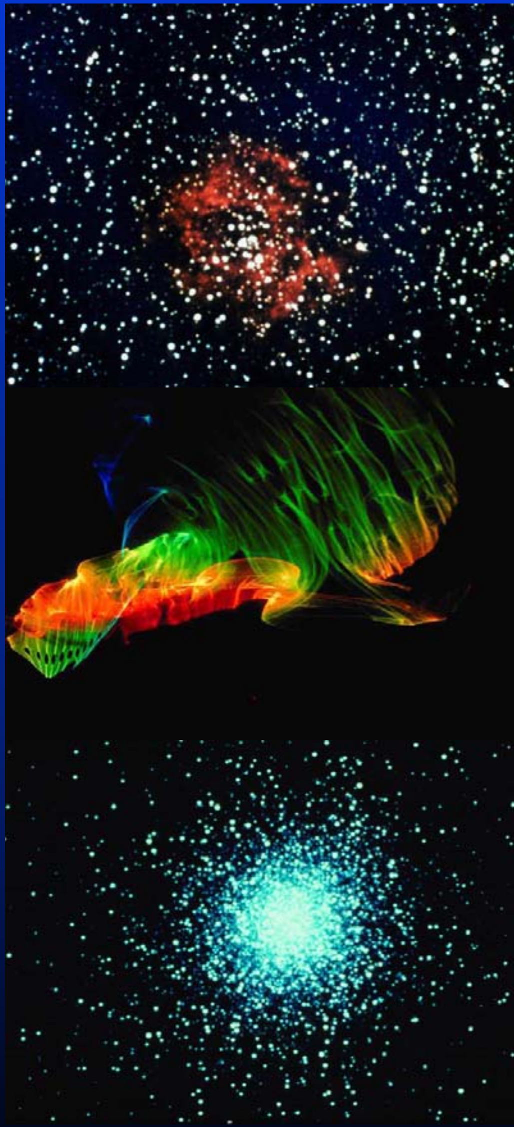
- Noise parameters:
  Factors that are beyond the control of the designer or too expensive to control or change
  - material property variability
  - manufacturing process limitations
  - environment temperature & humidity
  - component degradation with time
  - ...



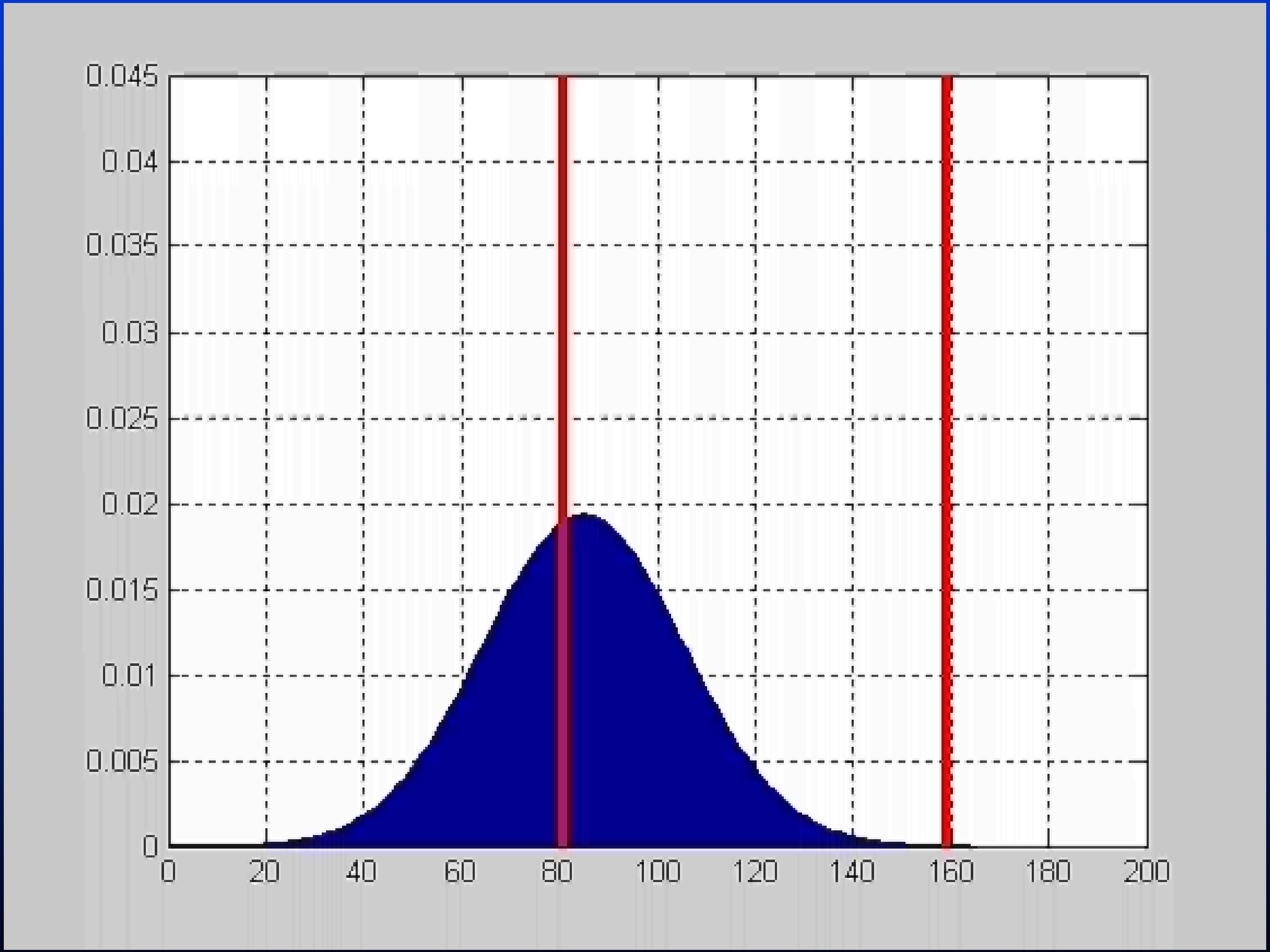
- Control Parameters:
  Factors that the designer can control
  - geometric design variables
  - material selections
  - design configurations
  - manufacturing process settings
  - ...

Tools for Robust Design

- Design Of Experiments
  - Exploits nonlinearities and interactions between noise & control parameters to reduce product performance variability
  - full factorial, fractional factorial, Monte-Carlo, LHC
- Response Surface Methods
  - Central Composite Design
  - Box-Behnken Design
- 6-sigma design
  - Identifying & qualifying causes of variation
  - Centering performance on specification target
  - Achieving Six Sigma level robustness on the key product performance characteristics with respect to the quantified variation

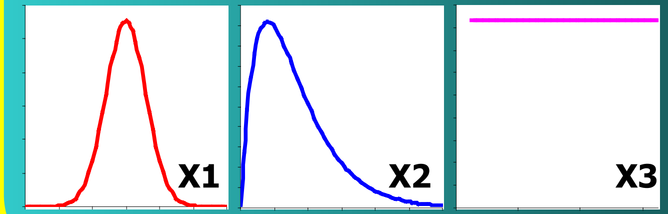


Shift and Squeeze



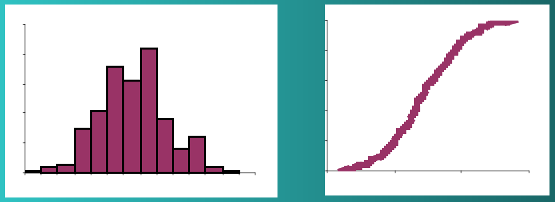
Statistical Design Performance Simulation

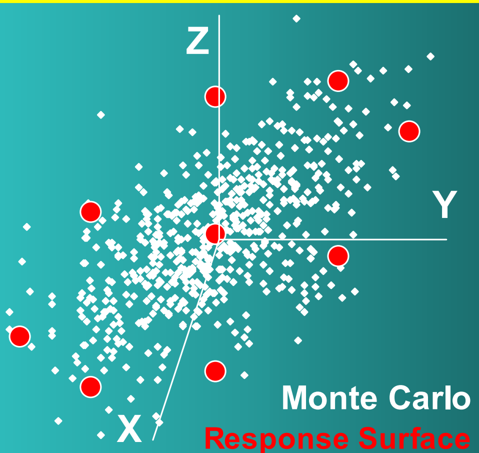
Simulation of input parameters (material, thickness, spot welds, …)



PDS

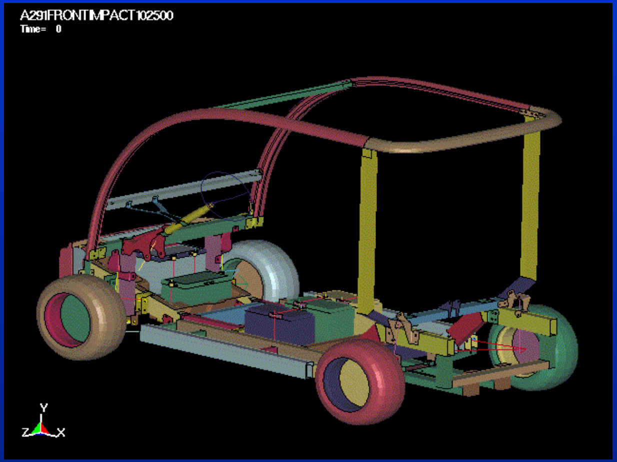
Statistical analysis of output parameters (stress, fatigue life, …)

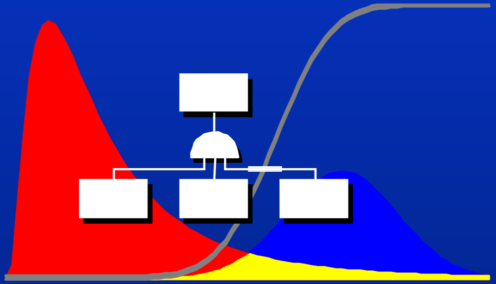


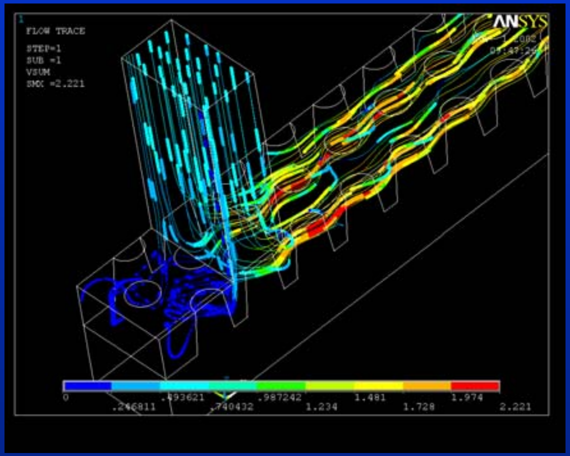


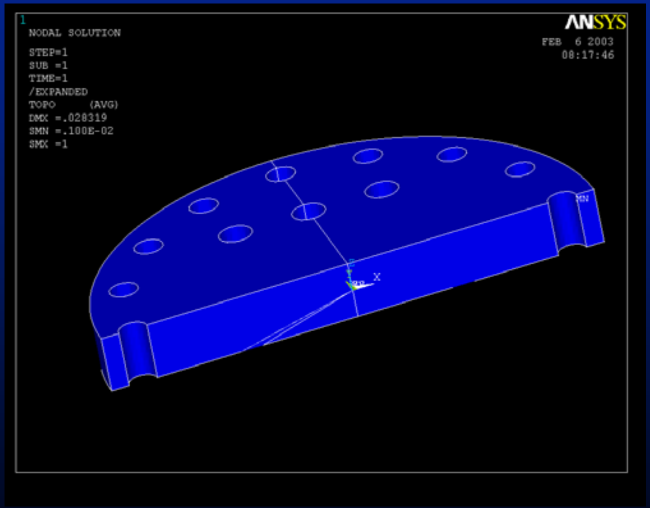
- **Over-design is avoided**
  (not “as planned“, “as is” or the “worst design”)
- **Weight Reduction**
- **Six sigma quality**

Program Overview









- Integration of the latest Computer Aided Engineering tools with advanced design techniques to solve key technical barriers and to accelerate the development process. We work closely with industry to identify technical challenges and provide innovative solutions.

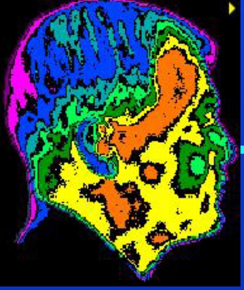
Digital Functional Vehicle

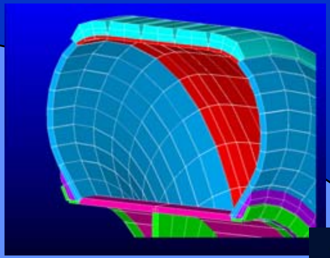
integrated engineering tools for enabling energy saving technologies

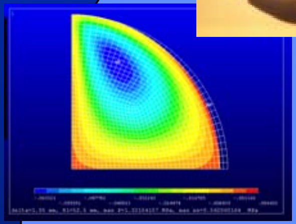
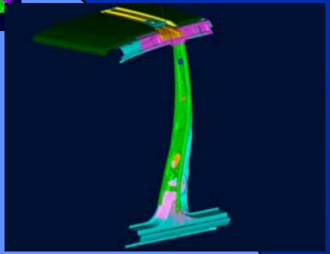
- Sampling from the NREL Tool Kit:
  - TRIZ & Topology Optimization for conceptual design
  - Parametric Behavioral Modeling CAD *(not dimension but attribute driven design)*
  - Finite Element Modeling (implicit, explicit, VPG)
  - Multi-physics applications *(structural/thermal, fluid/thermal, electromagnetics,etc)*
  - Optimization integrated with CAD & FEA
  - Design for 6-sigma using CAE (DFSS)
  - Probabilistic Design Methods *(engineering quality into designs)*
  - Experimental Design Techniques
  - Integration with Vehicle Systems Analysis tools
  - Engineering Resources and Computational Power Available at National Labs

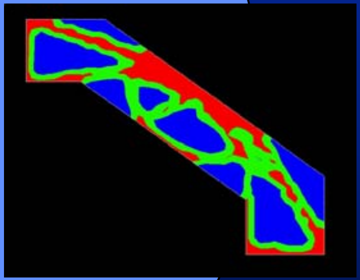
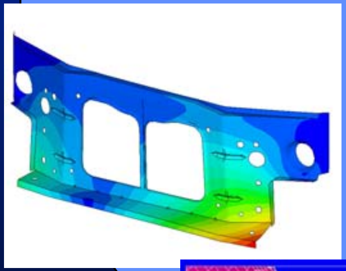
Recent DFV Applications

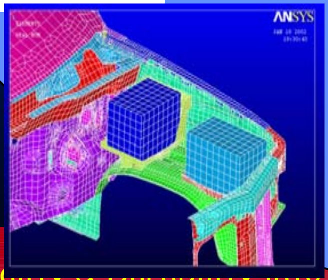
Petroleum Consumption, Technical Hurdles, Transfer to Industry

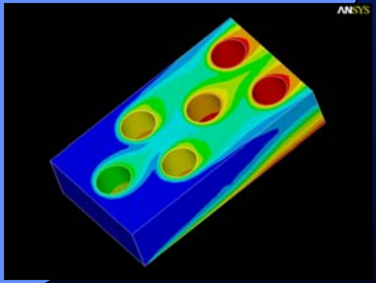


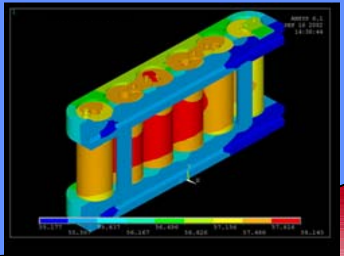



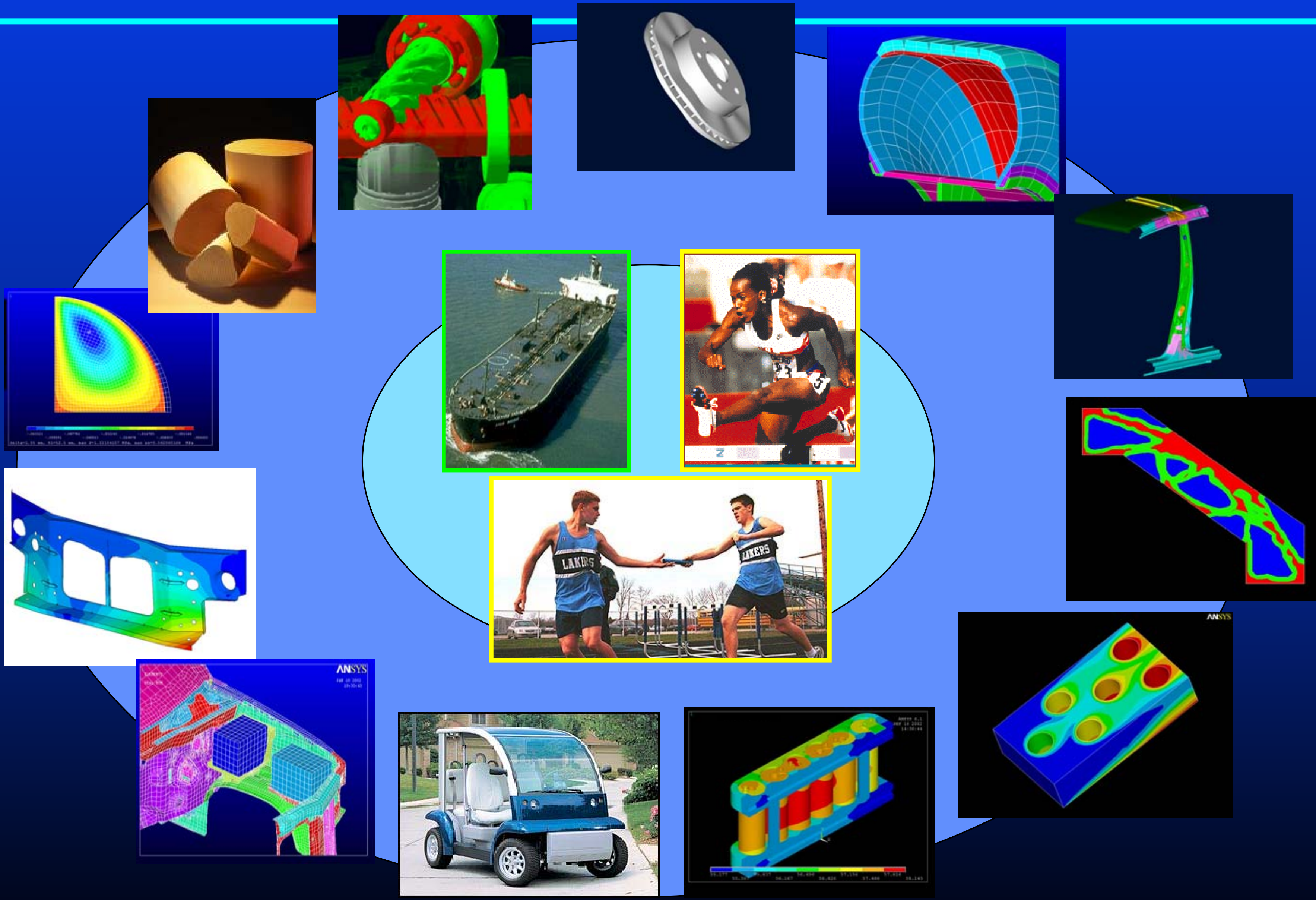



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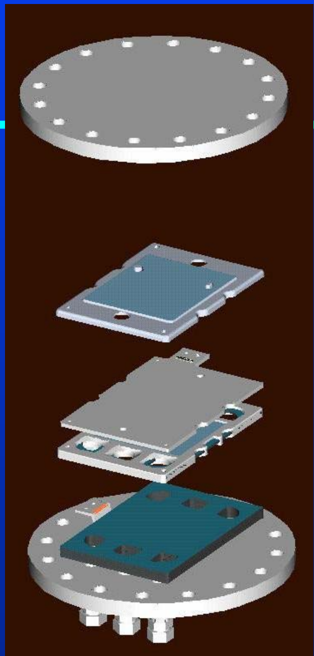
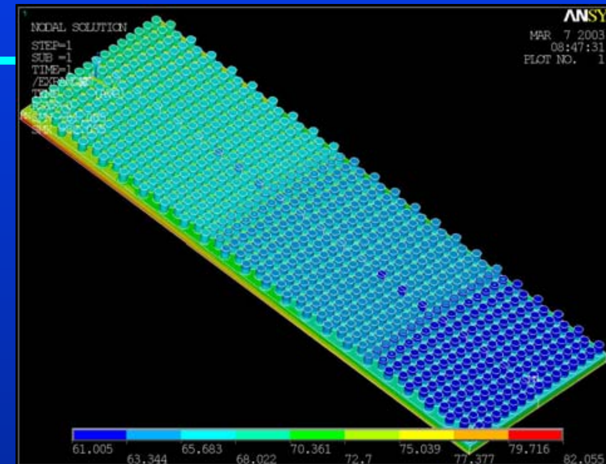


Robust Designs of Fuel Cell Components

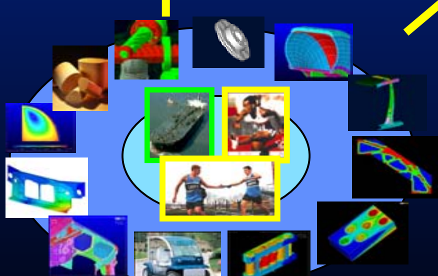
-Thermal analysis
-Structural analysis
-Topology optimization
- High temperature stack

- Plug Power



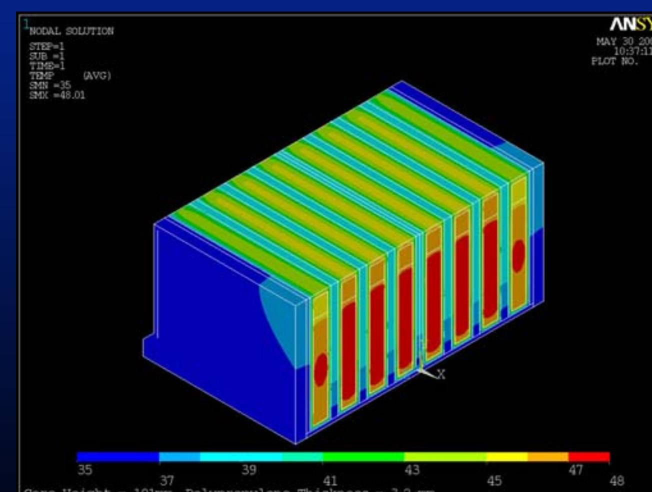
Behavioral Modeling for Power Electronics Cooling

- Ballard Power Systems



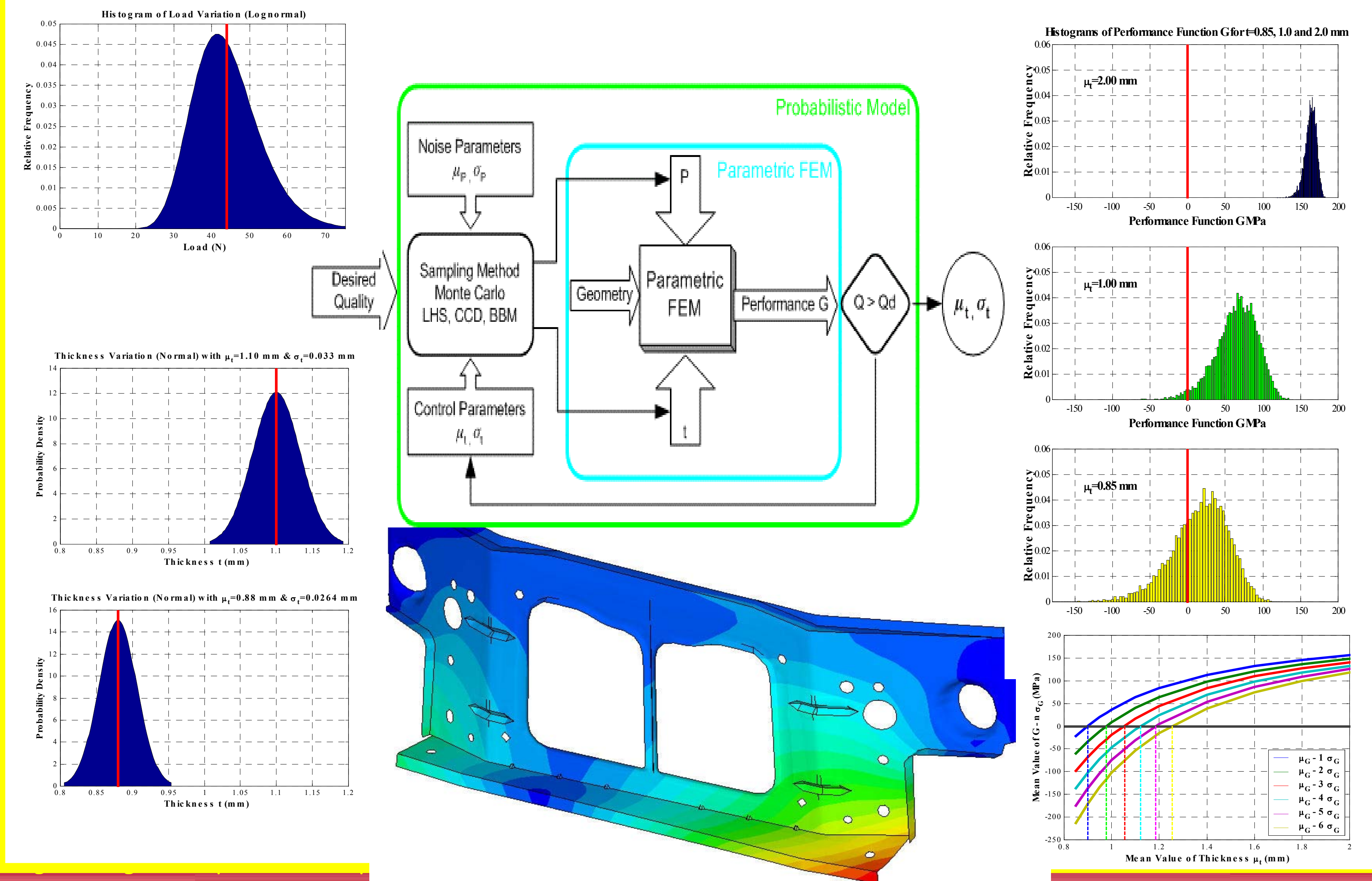
Design for Six-sigma Techniques for Battery Thermal Management

- Ford Motor Co - USABC

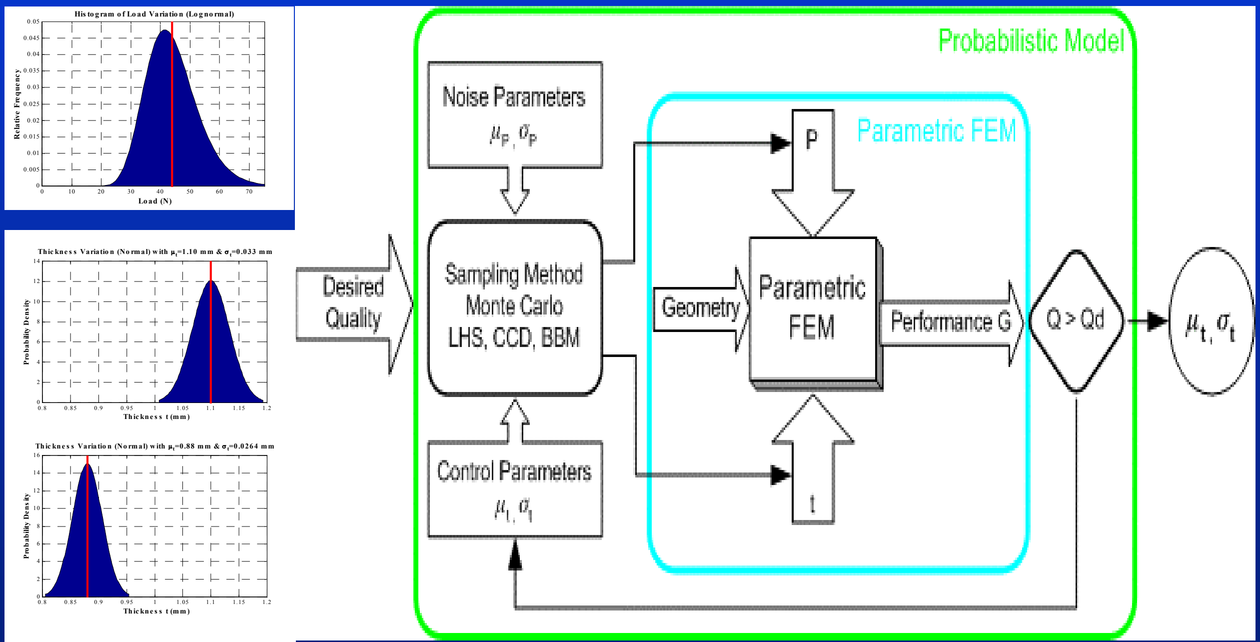


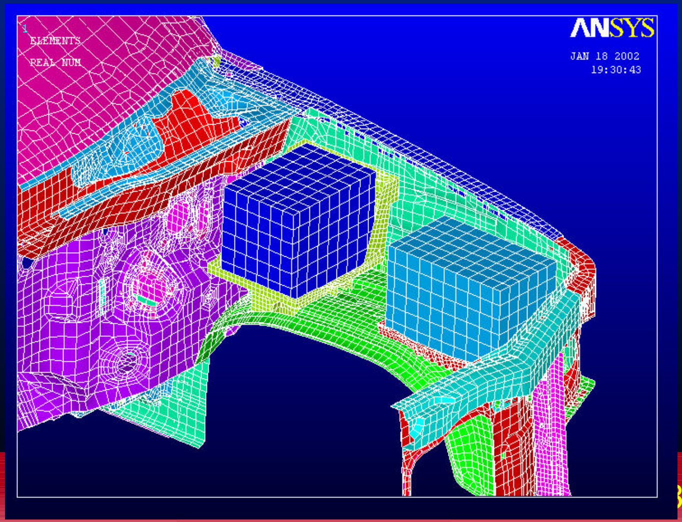
Robust Optimization

light weight designs with 6σ quality



Robust Optimization **reusable** workflow template

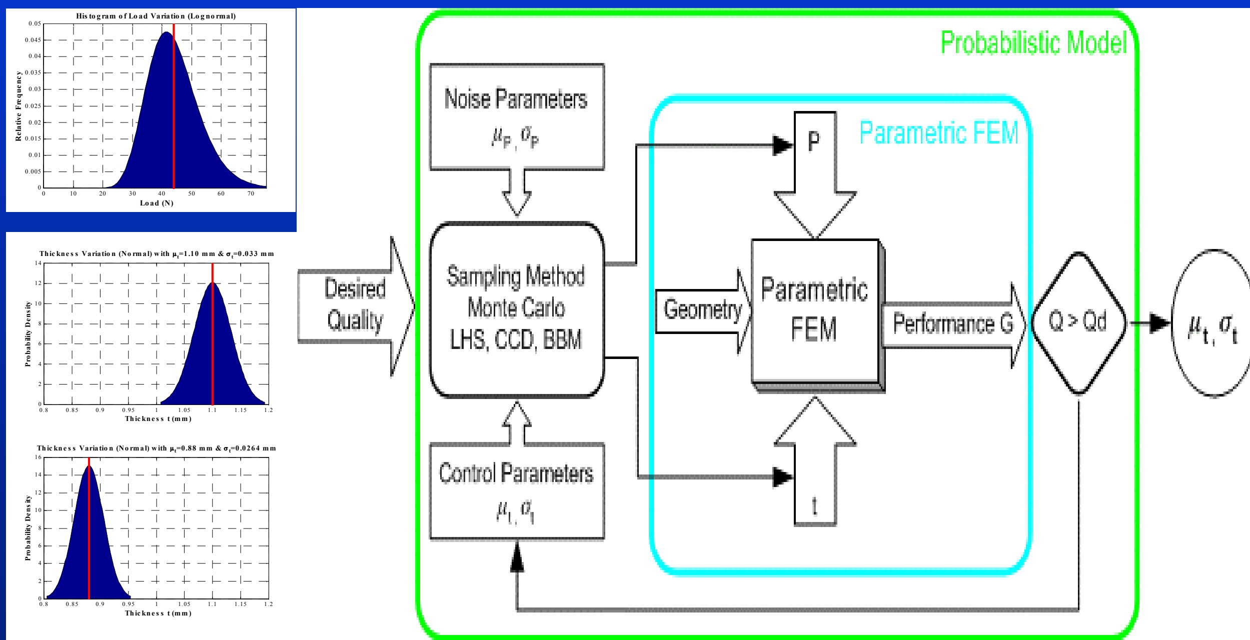


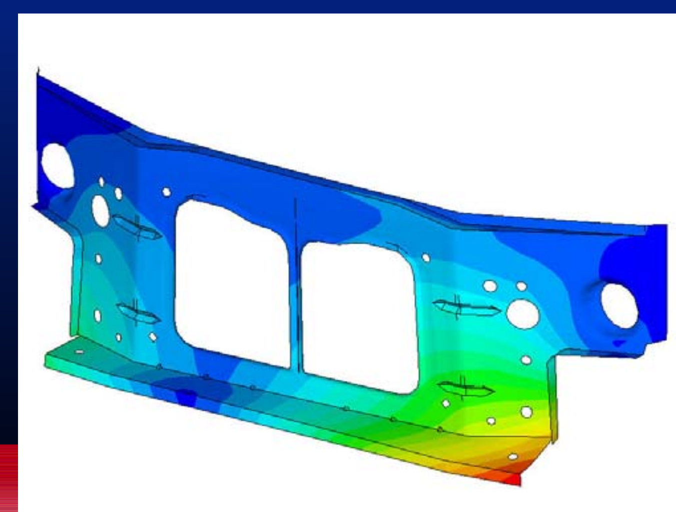


Ford Motor Company

SAE – IEBEC 2001

Robust Optimization **reusable** workflow template

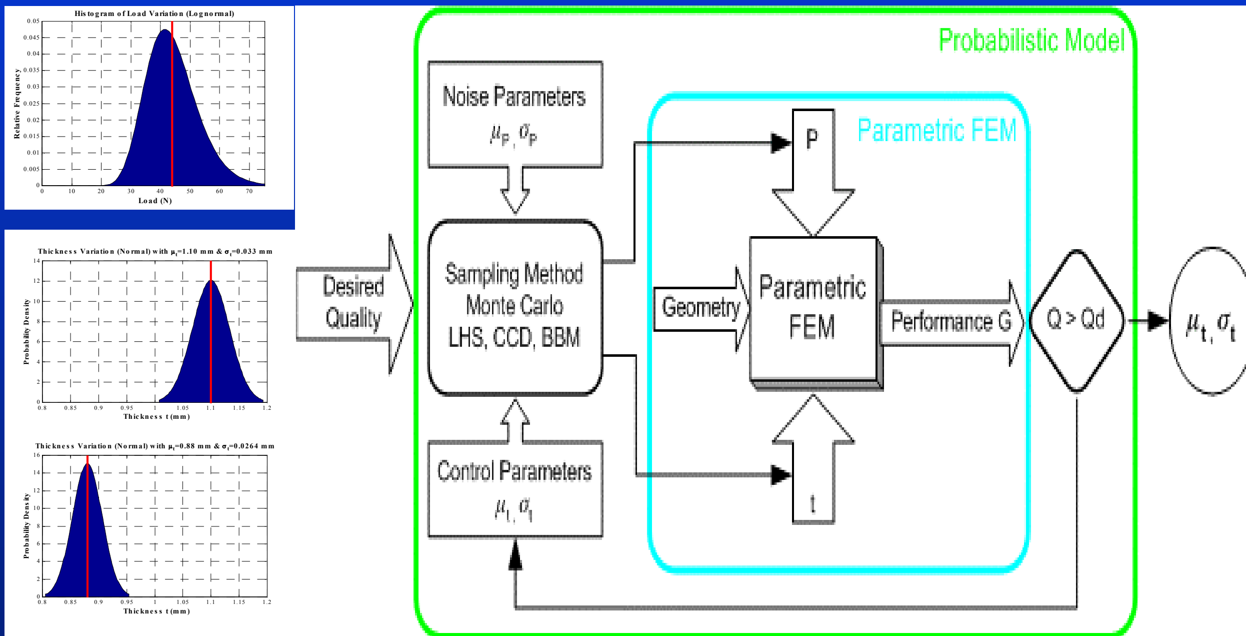


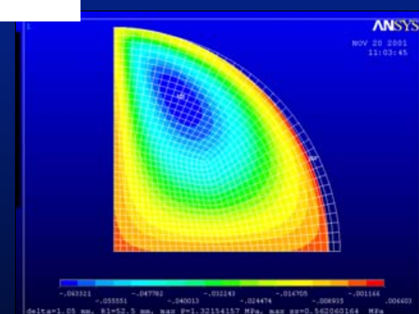


Ford Motor Company

SAE – IEBEC 2002

Robust Optimization reusable workflow template

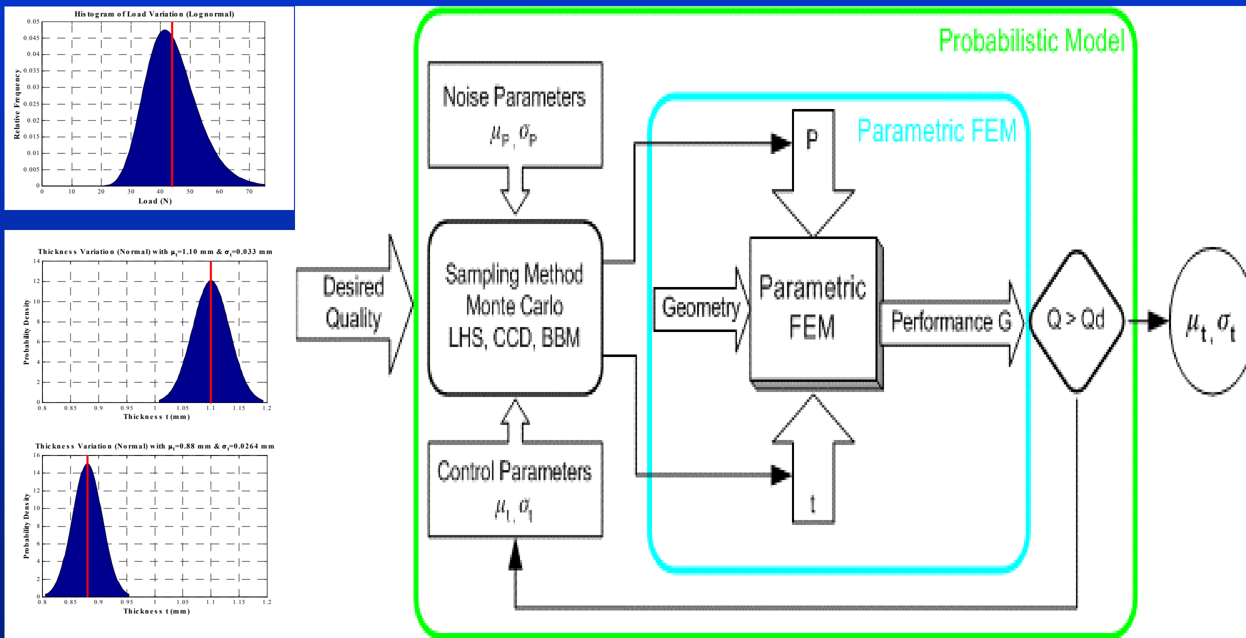


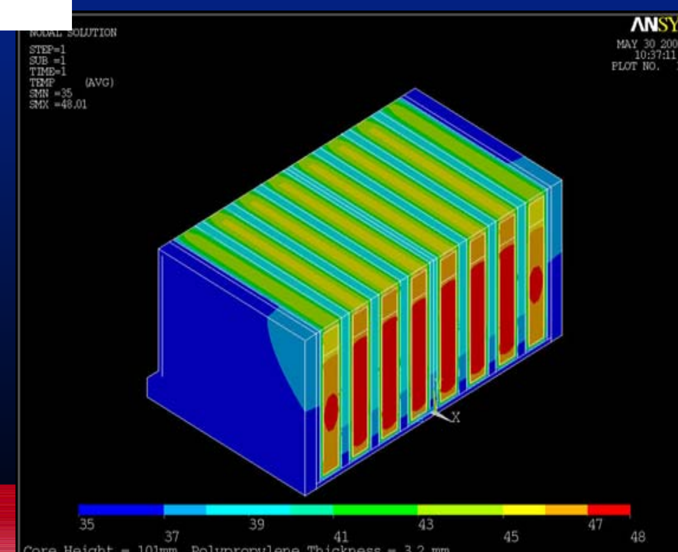


Daimler Chrysler

SAE Powertrain Conference

Robust Optimization **reusable workflow template**





USABC / Ford

American Society of Quality

Transferring the Tools to Industry

02FCC-51

Energy Efficient Battery Heating in Cold Climates

Andreas Vlahinos, Ph.D.
Principal, Advanced Engineering Solutions

Ahmad A. Pesaran, Ph.D.
National Renewable Energy Laboratory

Reliability Based Optimization within the CAD Environment

Andreas Vlahinos
Advanced Engineering Solutions, LLC
Subhash Kelkar
Ford Motor Company
Stefan Reh, Robert SeCaur, Steve Pilz
ANSYS Inc.

Abstract

Great advances have been achieved over the … this process is still executed by deploying … accommodate potentially contradictory desi… life cycle, and environmental impacts is bei… technically less adept competitors.

02IBECA-28

Designing For Six-Sigma Quality with Robust Optimization using CAE

Andreas Vlahinos, Ph.D.
Principal, Advanced Engineering Solutions, LLC

Subhash G. Kelkar, Ph.D.
Staff Technical Specialist, Ford Motor Company

01IBECA-6

Body-in-White Weight Reduction via Probabilistic Modeling of Manufacturing Variations

Andreas Vlahinos, Ph.D.
Principal, Advanced Engineering Solutions, LLC

Subhash Kelkar, Ph.D.
Staff Technical Specialist, Ford Motor Company

First International Conference on Fuel Cell Science, Engineering and Technology
April 21-23, 2003, Rochester, New York, USA

ASME International

EFFECT OF MATERIAL AND MANUFACTURING VARIATIONS ON MEAS PRESSURE DISTRIBUTION

Andreas Vlahinos[1], Kenneth Kelly[2], Jim D'Aleo[3], Jim Stathopoulos[4],

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02FCC-68

Robust Design of a Catalytic Converter with Material and Manufacturing Variations

Andreas Vlahinos
Principal, Advanced Engineering Solutions, LLC

Danet Suryatama, Mustafa Ullahkhan, Jay T. TenBrink, Ronald E. Baker
DaimlerChrysler Corporation

ABSTRACT

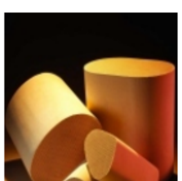
A design is robust when the performance targets have been achieved and the effects of variation have been minimized without eliminating the causes of the variation such as manufacturing tolerances, material properties, environmental temperature, humidity, operational wear etc. In recent years several robust design concepts have been introduced in an effort to obtain optimum designs and minimize the variation in the product characteristics [1,2]. In this study, a probabilistic design analysis was performed on a catalytic converter substrate in order to determine the required manufacturing tolerance that results in a robust design. Variation in circularity (roundness) and the ultimate shear stress of the substrate material were considered. The required manufacturing tolerance for a robust design with 1,2 and 3 sigma quality levels was determined. The same manufacturing tolerance for a reliability based design with reliability levels of 85%, 90% and 95% was also determined and compared. The methodology for implementing robust design used in this research effort is summarized in a reusable workflow diagram.

INTRODUCTION

Robust design is a methodology that addresses product quality issues early in the design cycle. The goal of …

of available resources. The probabilistic design process has not been widely used because it has been intimidating and tedious due to its complexity.

In this research effort, probabilistic modeling of manufacturing and material variations for a catalytic converter substrate was considered. Typical shapes of catalytic converter substrates are shown in Figure 1. The substrate used in this study has a cylindrical cross section and is enclosed in a cylindrical steel cover. If the substrate is not a perfect cylinder the steel cover applies a non-uniform pressure along the circumference. Assuming that the maximum diameter of the substrate is Φ_{max} and the minimum diameter is Φ_{min}, we can characterize the variation in circularity or roundness δ with their difference $\delta = \Phi_{max} - \Phi_{min}$. Due to manufacturing variations δ is considered a random input variable.



ASQ TECHNICAL PAPER SERIES

American Society for Quality ASQ

Empowering Engineers to Generate Six-Sigma Quality Designs

Andreas Vlahinos
Advanced Engineering Solutions, LLC

Kenneth Kelly, Ahmad Pesaran & Terry Penney
National Renewable Energy Laboratory

Press & Analyst Community

"Engineering Quality into Digital Functional Vehicles," IDPS2002, 2002 June 2002

"Mixing CAD with simulation gives designers new power" September 2002 Machine Design Magazine

"The Probability of Optimum Design" October 2002 Desktop Engineering Magazine

"The Probability of Quality" March 2003 Desktop Engineering Magazine


MACHINE DESIGN

September 2002

CAD

A dialog box from PTC's Behavioral modeling extension shows the optimization setup with a goal of minimum weight. The lower portion shows design variables and their limits for a box beam. Optimization is easily substituted for a sensitivity study that determines and plots effects of any Pro/E design variable to the natural frequency, or the probability of failure..

Another example for a battery tray finds the sensitivity and response distribution (stress, stiffness, fatigue life) from the scatter of several variables, such as modulus of elasticity, thickness, and loading, when they are defined in terms of probability distribution functions. Monte Carlo and response-surface sampling determine the response distribution. Six-sigma design criteria can be used to size the components and compare this design to one developed using traditional nominal-value figures. The example uses a battery, composite tray, and interface elements. The automatic reliability-based optimization reduced the tray's weight by 17%.

Mises stresses for one load case. Users can ask for a screen capture of such a display. From the display option, users choose other load cases for which they need graphs, plots, and images.

In addition, the software presents general results such as maximum, minimum, and average for requested values. Information and explanations are in French, so there is no misunderstanding. And automated HTML reports of analyses can be sent to others.

MIXING CAD WITH SIMULATION GIVES DESIGNERS NEW POWER

Combining the analysis capabilities of two independent design programs let designers with **Ford Motor Co.** go from functional goals and sizing parameters to the best designs that meet the company's quest for six-sigma quality. The software packages are Behavioral Modeling Extension (BMX) from **PTC,** Needham, Mass. (*www.PTC.com*), and Ansys Probabilistic Design System (PDS) from **Ansys Inc.,** Cannonsburg, Pa. (*www.ansys.com*)

BMX lets designers start with a goal and a few constraints. For instance, a bottle might need to hold exactly a quart and not exceed a particular height, width, or length. BMX in Pro/E calculates many containers that meet the goal and presents the results in a graph. The designer then selects a best one. "BMX drives designs through engineering requirements instead of dimensions, as most are," says Andreas Vlahinos, Principal of Advanced Engineering Solutions LLC, Castle Rock, Colo.

PDS software, on the other hand, lets user consider variability in material properties and dimensions. This lets users answer questions such as: If input variables for a simulation model fall within a range, what is the scatter of the output values? Or, which input variables contribute most to the scatter of an output parameter and to the probability of failure? "You can ignore variations and pay later, or incorporate them in the design and analysis and get an expected behavior," says Vlahinos.

For example, a designer can change a hole in a radiator support and the combined software package updates the bracket thickness to meet a quality criteria and minimum weight. "A good analyst with lots of time can do this already," says Vlahinos, "But it's too complex for a designer at early formation stages."

Geometric dimensions, such as the average part thickness can be controlled by designers. Uncontrollable or noise factors such as manufacturing imperfections (standard deviation of the thickness), environmental variables (loading), or product deterioration (material properties) are sources of variations that cannot be eliminated, explains Vlahinos. A rugged design should reduce a product's variation by reducing its sensitivity to the sources of variation rather than by *controlling* the sources.

Ford engineers would like designers to produce the same work as experienced analysts. To this end, they have collaborated with Vlahinos to integrate BMX and PDS. "We developed a little program with a lot of brains behind it that's usable by designers," he says. "Essentially, we automatically capture and reuse the expert's knowledge. This way, when designers shape something, certain design variables update automatically to assure that the design meets certain quality criteria. "Six-sigma has been implemented effectively in management and these techniques let us introduce six-sigma methods into engineering design." ■

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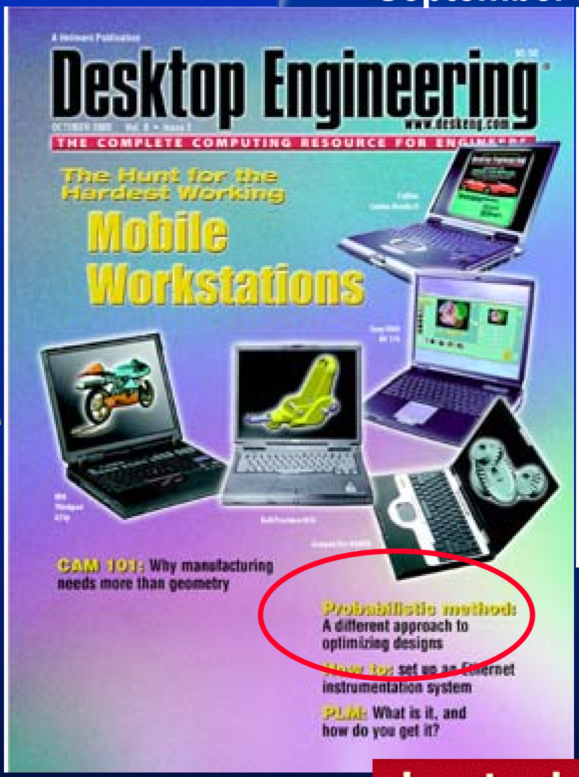

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Intelligent Digital Prototyping Strategies

Outline

- Introduction to Engineering Quality
- Program Overview
- Applications:
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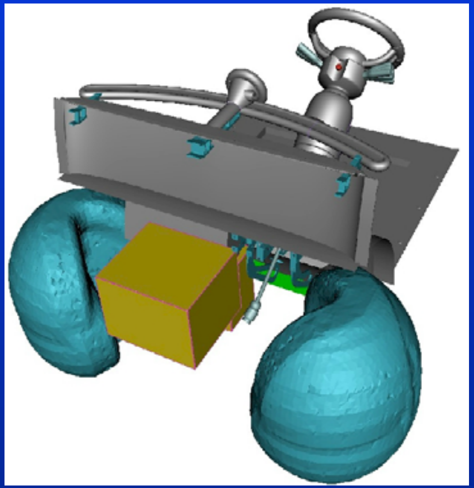
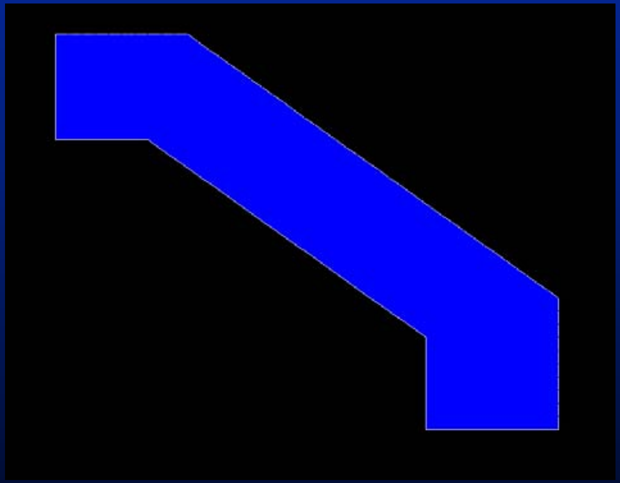
FORD Think Mobility Design Optimization

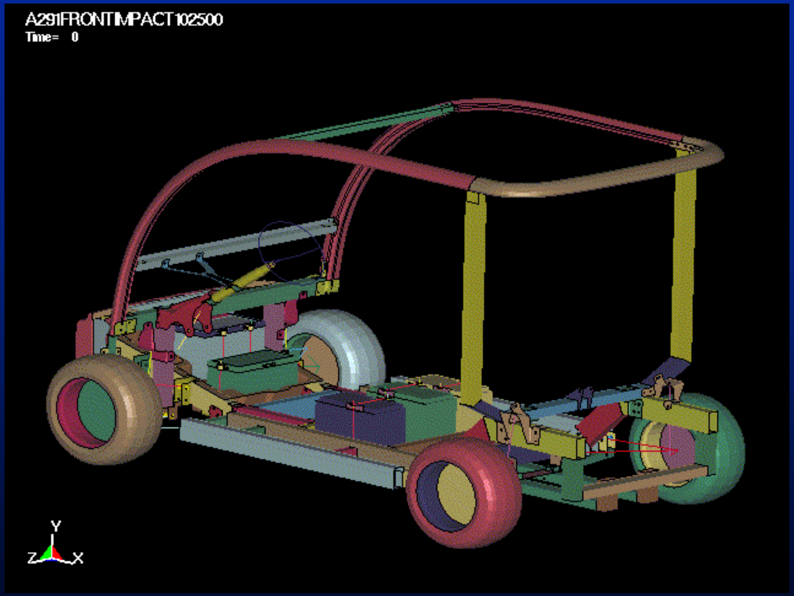
Time to Market

Space Claim
Envelope
Suspension
Optimization





Topology Optimization



Crash Simulation

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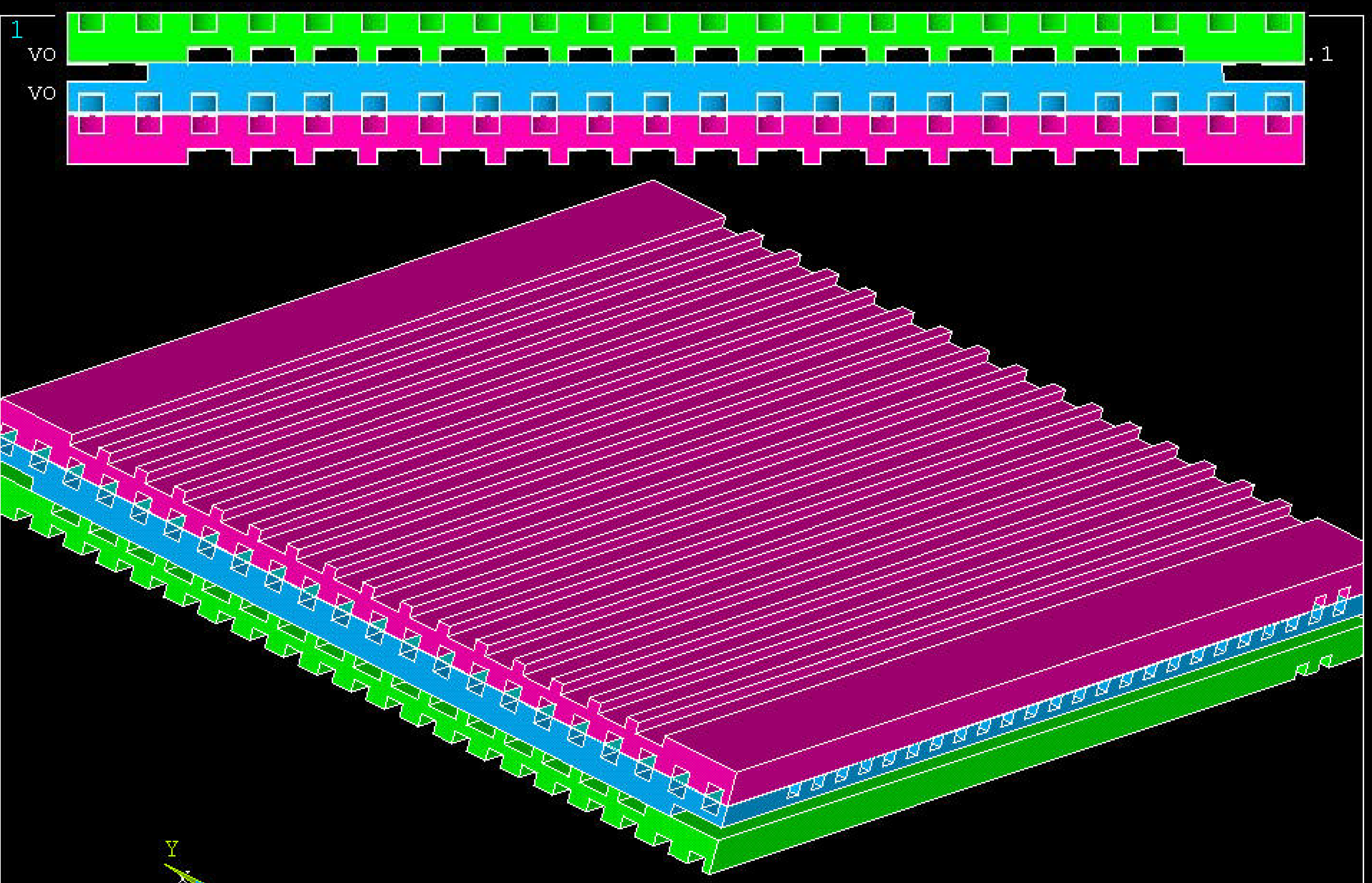
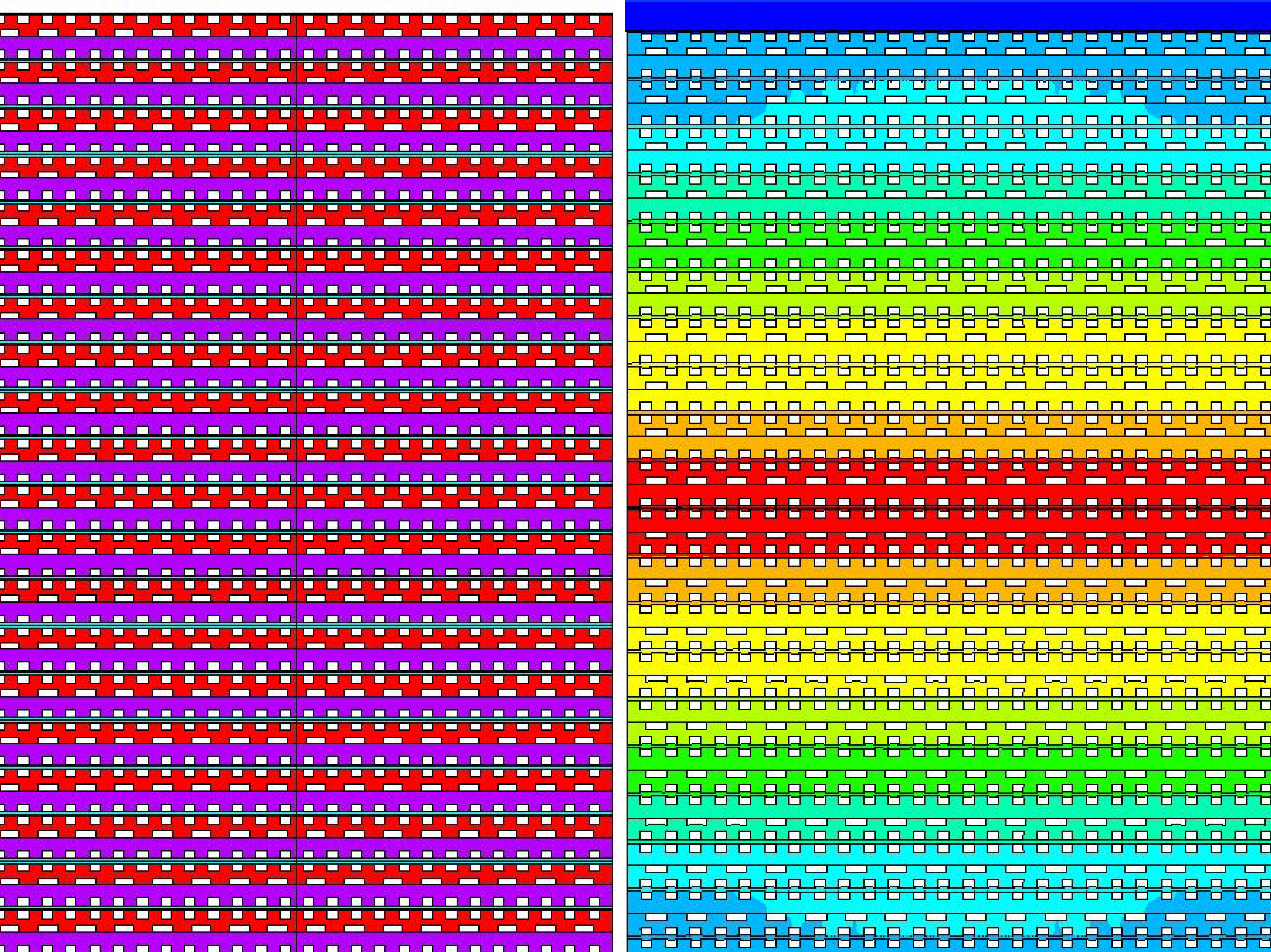
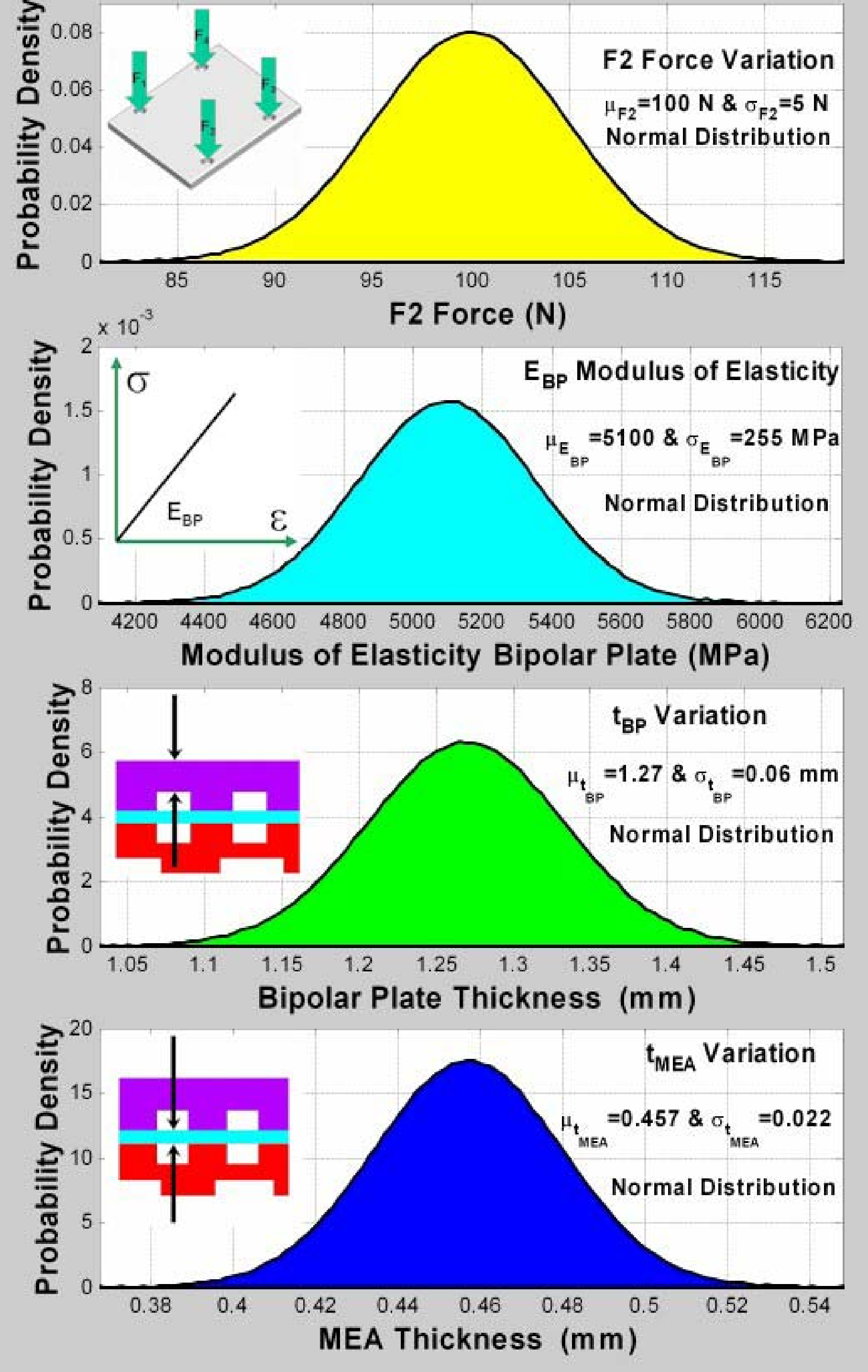
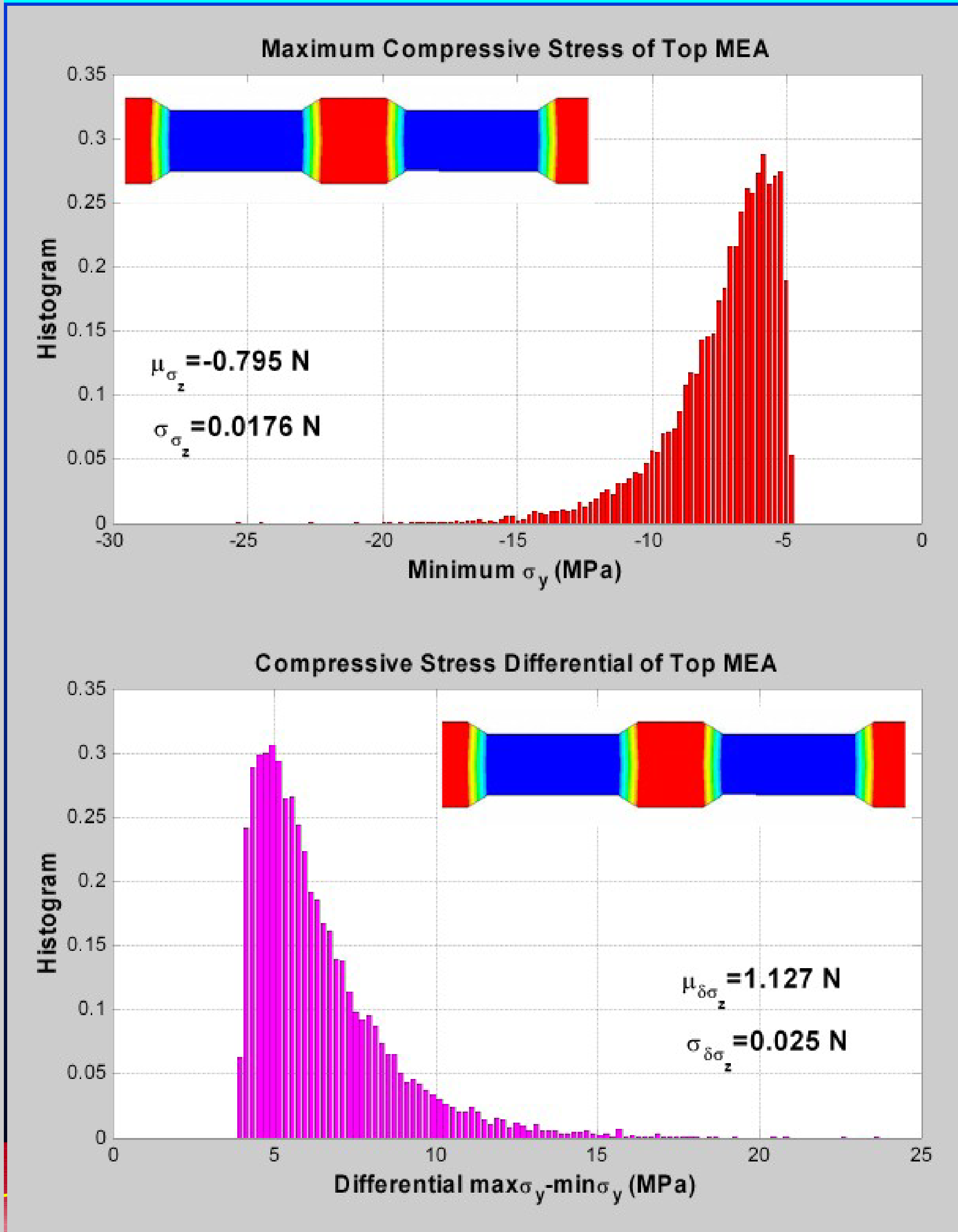
Robust Design of Fuel Stack

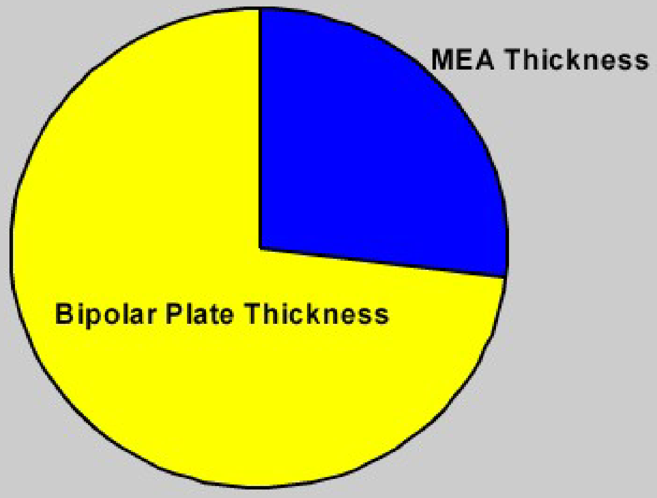


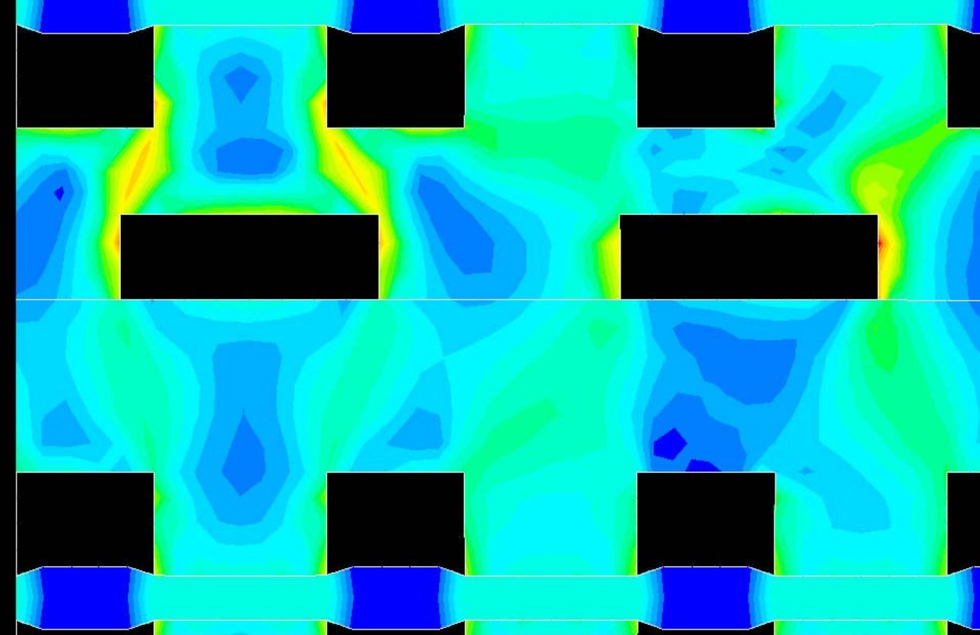



F2 Force Variation
μ_{F2}=100 N & σ_{F2}=5 N
Normal Distribution
Probability Density
F2 Force (N)
E_{BP} Modulus of Elasticity
$\mu_{E_{BP}}$=5100 & $\sigma_{E_{BP}}$=255 MPa
Normal Distribution
x 10^{-3}
σ
ε
E_{BP}
Probability Density
Modulus of Elasticity Bipolar Plate (MPa)
t_{BP} Variation
$\mu_{t_{BP}}$=1.27 & $\sigma_{t_{BP}}$=0.06 mm
Normal Distribution
Probability Density
Bipolar Plate Thickness (mm)
t_{MEA} Variation
$\mu_{t_{MEA}}$=0.457 & $\sigma_{t_{MEA}}$=0.022
Normal Distribution
Probability Density
MEA Thickness (mm)

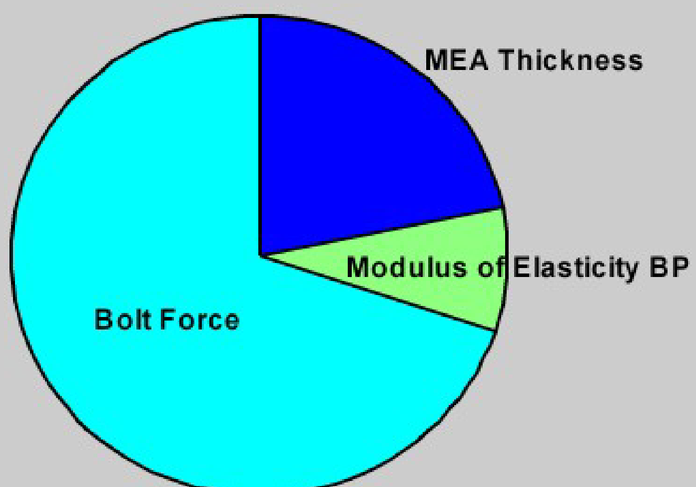

Maximum Compressive Stress of Top MEA
Histogram
μ_{σ_z}=-0.795 N
σ_{σ_z}=0.0176 N
Minimum σ_y (MPa)
Compressive Stress Differential of Top MEA
Histogram
$\mu_{\delta\sigma_z}$=1.127 N
$\sigma_{\delta\sigma_z}$=0.025 N
Differential maxσ_y-minσ_y (MPa)

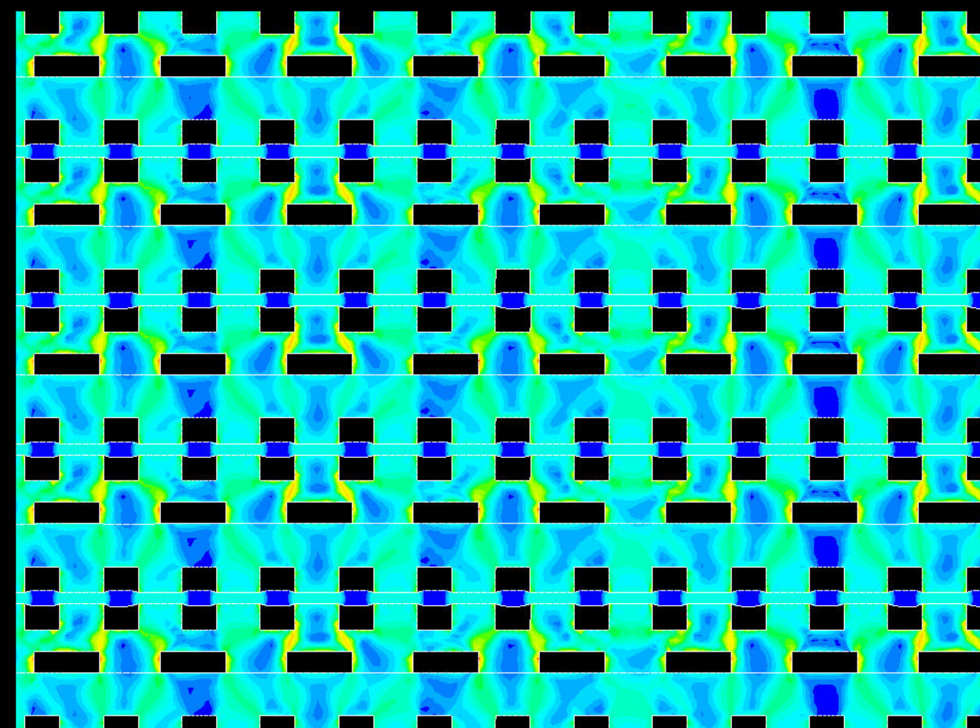
Sensitivity of Design Variables on Pressure Uniformity $\Delta\sigma_z$ of First Membrane





Sensitivity of Design Variables on Pressure Uniformity $\Delta\sigma_z$ of Middle Membrane





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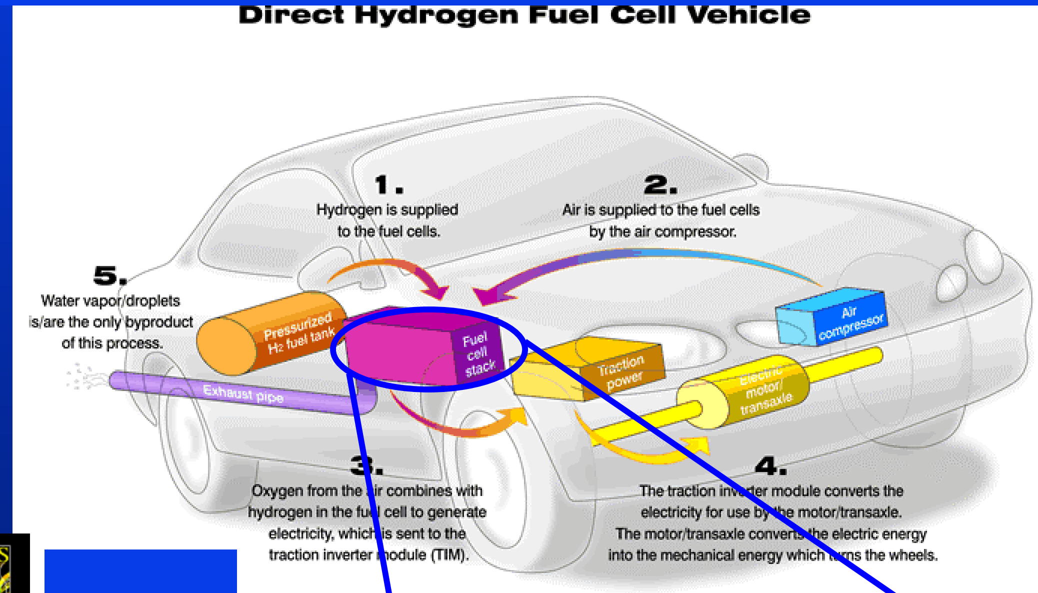
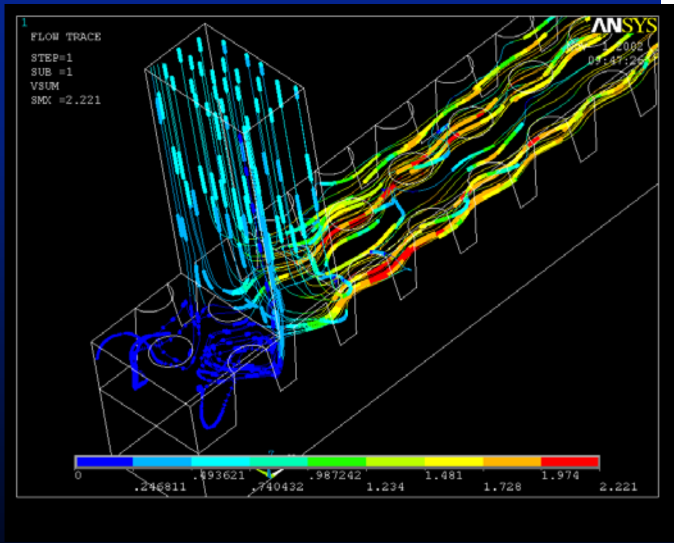
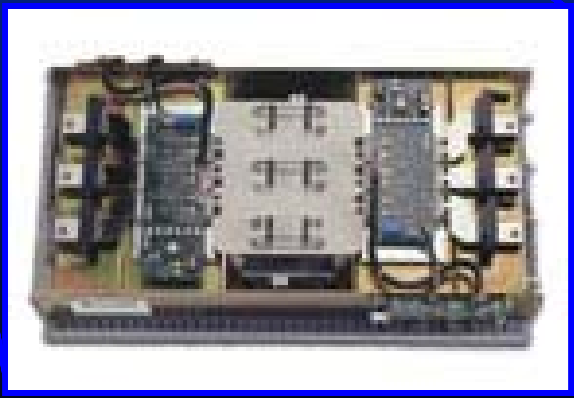
Power Electronics Cooling with Behavioral Modeling
Enabling Critical Technologies

Multi-Physics Modeling

conjugate solutions of thermal,
structural,
fluid-flow,
electromechanical problems







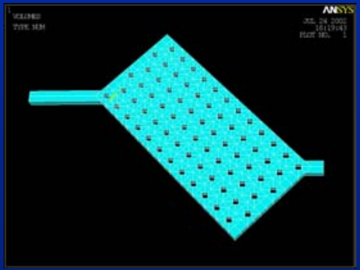
Power Electronics Cooling with Behavioral Modeling

Project Goal :

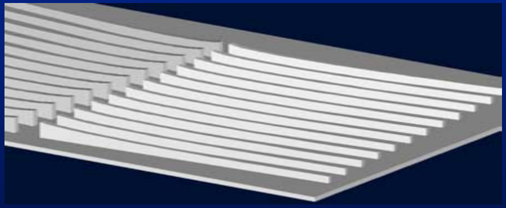
Develop a heat exchanger design to efficiently remove heat from AIPM and reject it into the vehicles coolant loop with uniform cooling, minimum cost, volume and pressure drop.

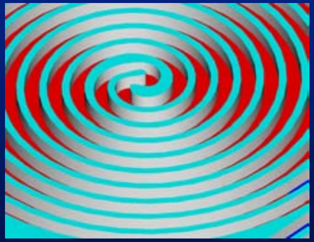
Objective:

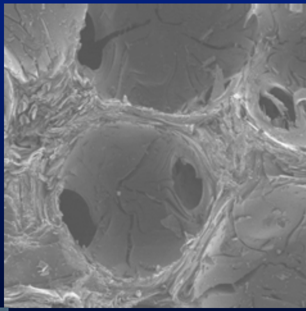
Identify which cooling concept the NREL team should pursue further:

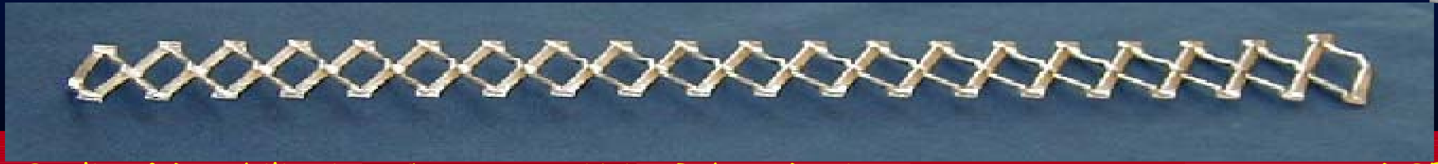


1. Pin-Finned Design
2. “Cook-top” serpentine flow field
3. “Fish bone” fins
4. Carbon Foam
5. Aluminum Extrusion with Expanded Metal Turbulator

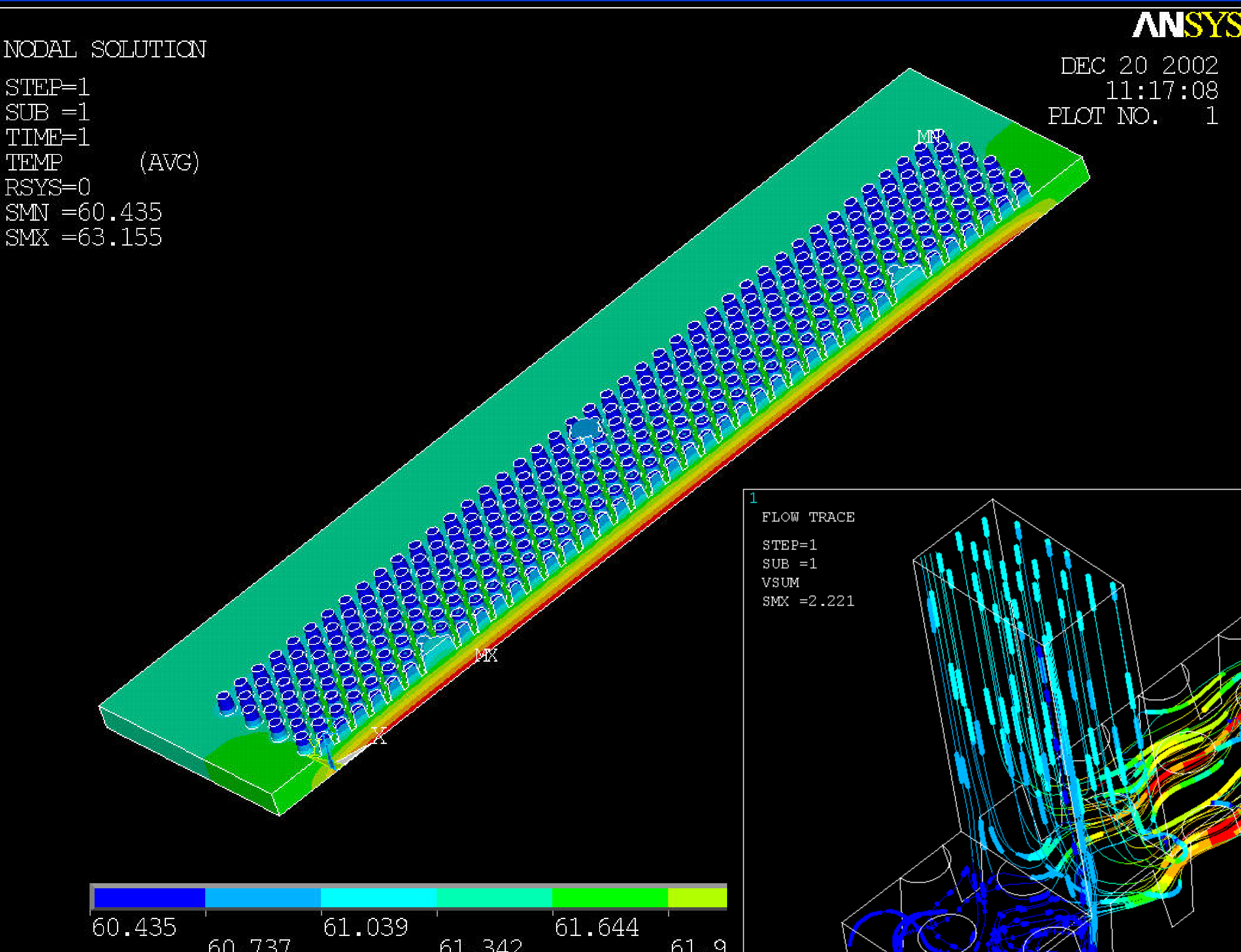


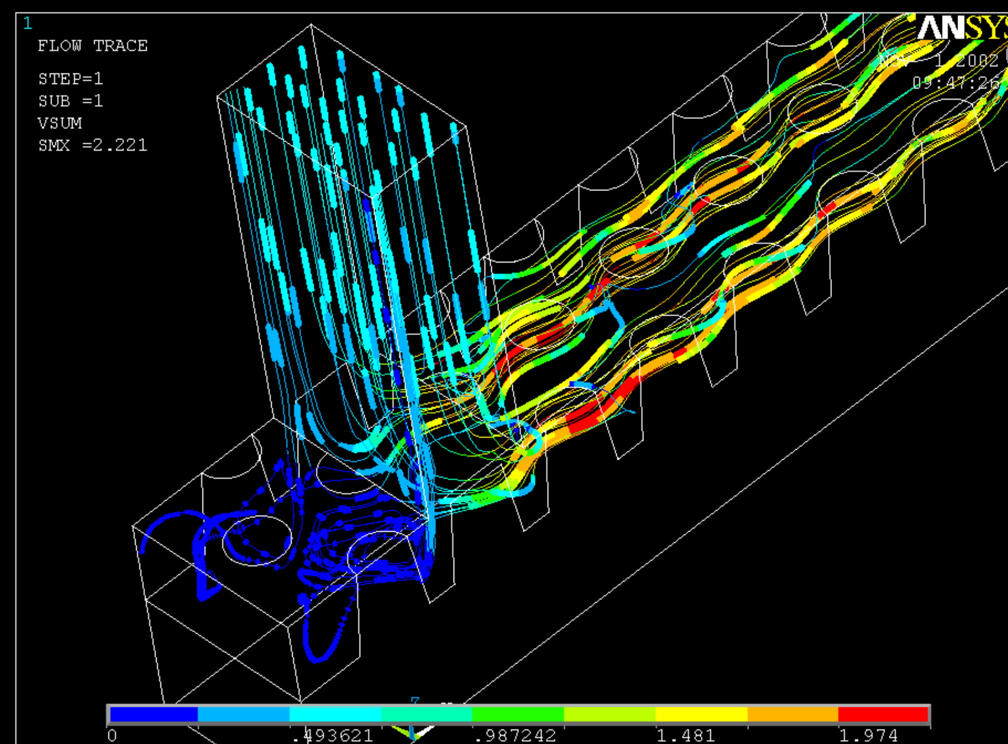


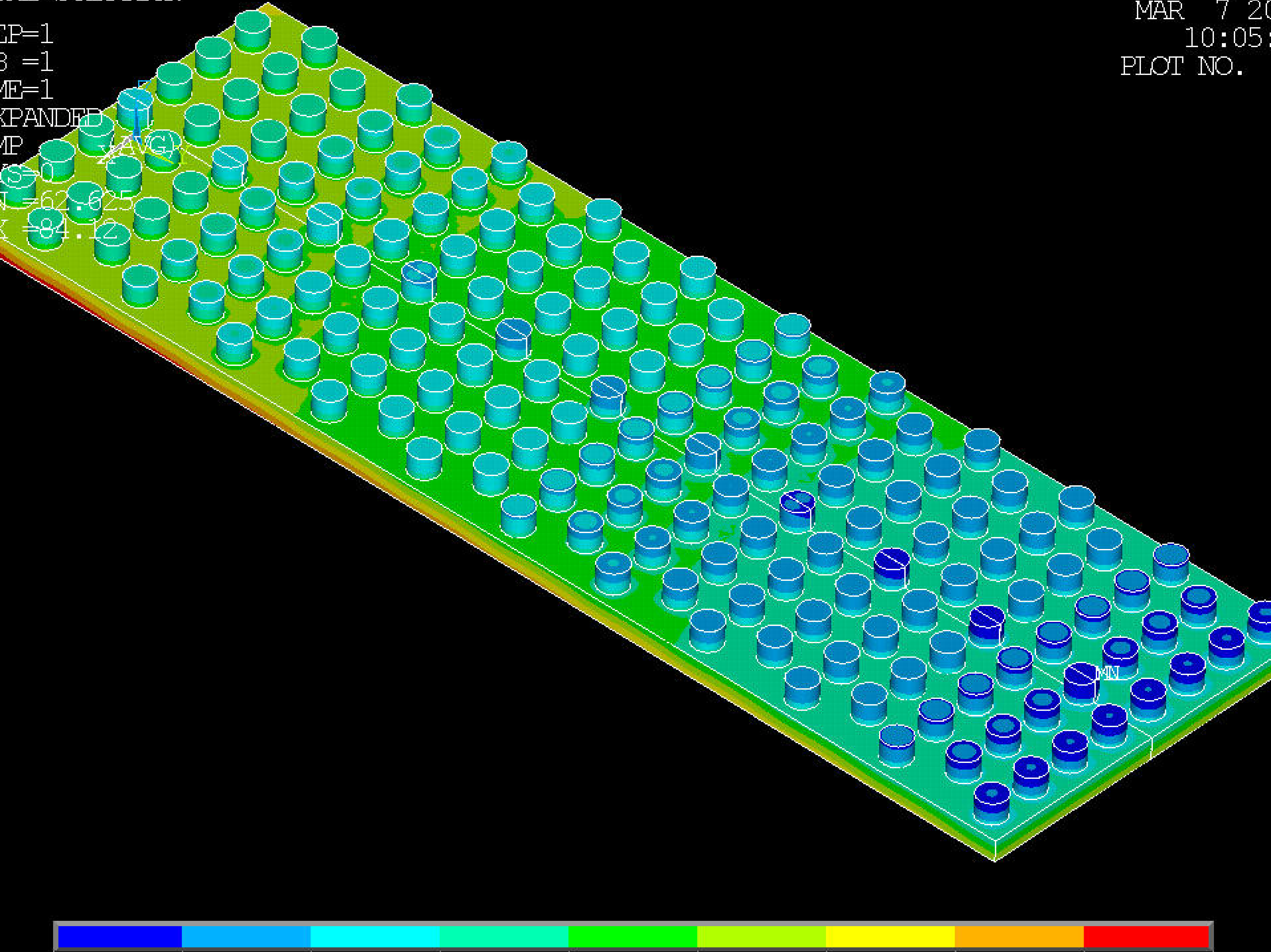




Conjugate Solution of CFD and Heat Transfer







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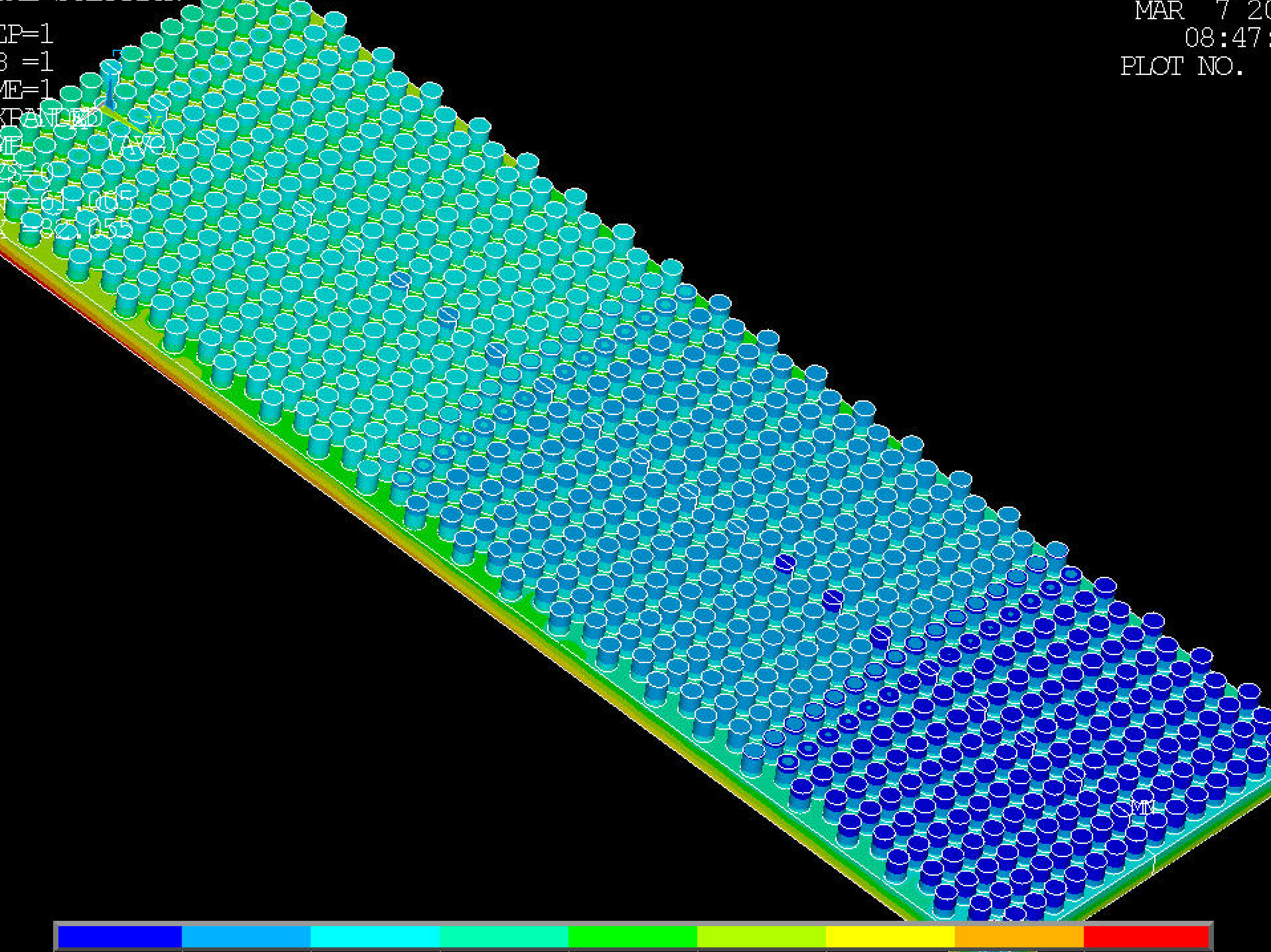
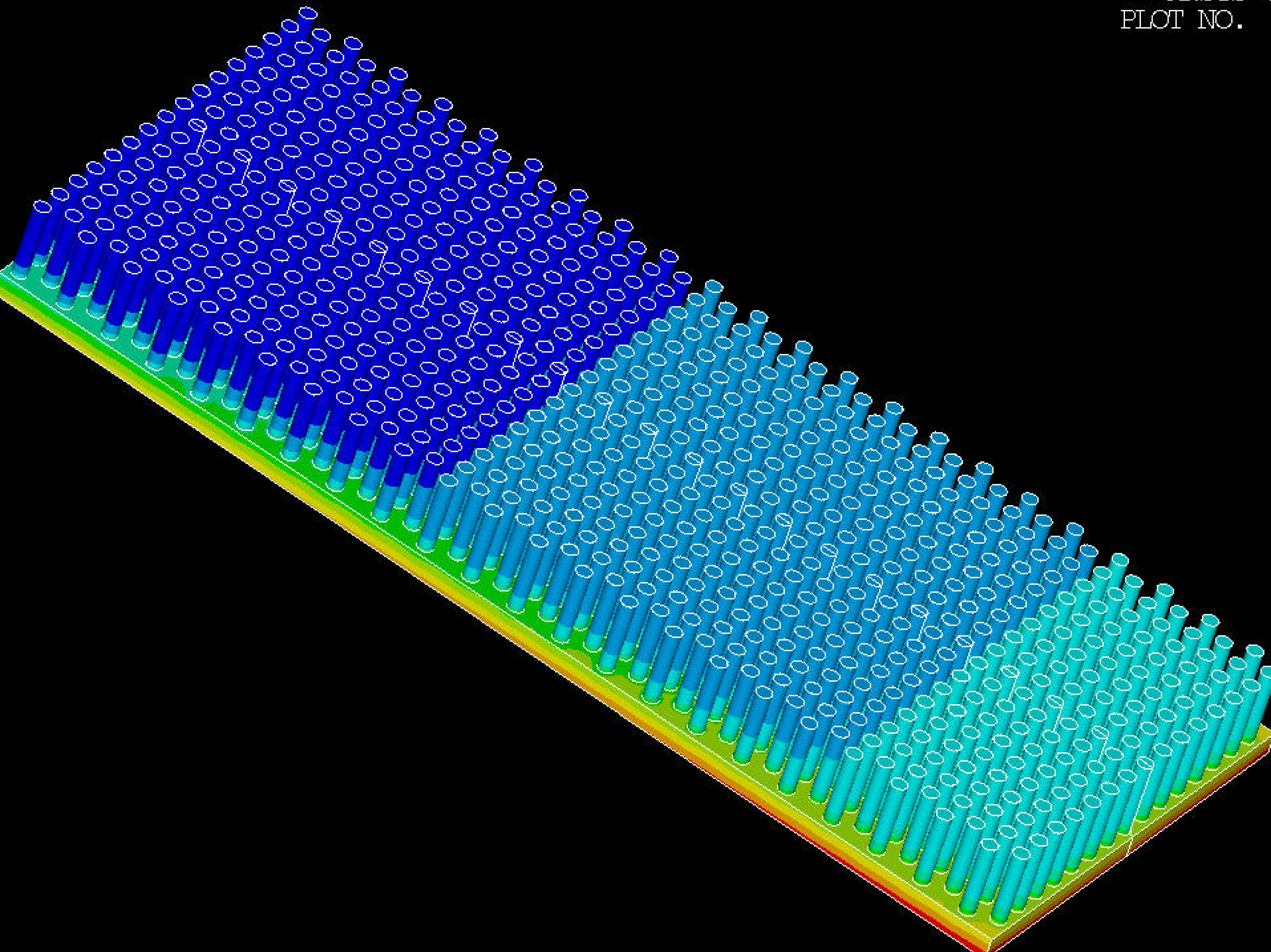
B =1
ME=1
XPANDED
(AVG)
=62.625
=84.12
MAR 7 20
10:05:
PLOT NO.
MN


MAR 7 20
08:47:
PLOT NO.
MN


PLOT NO.

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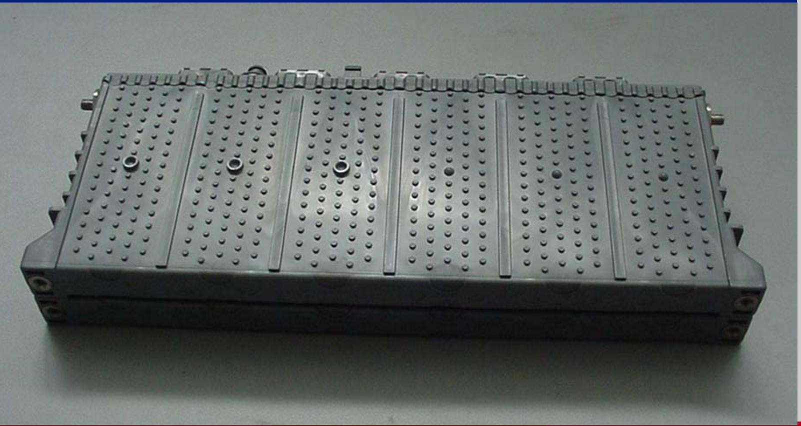
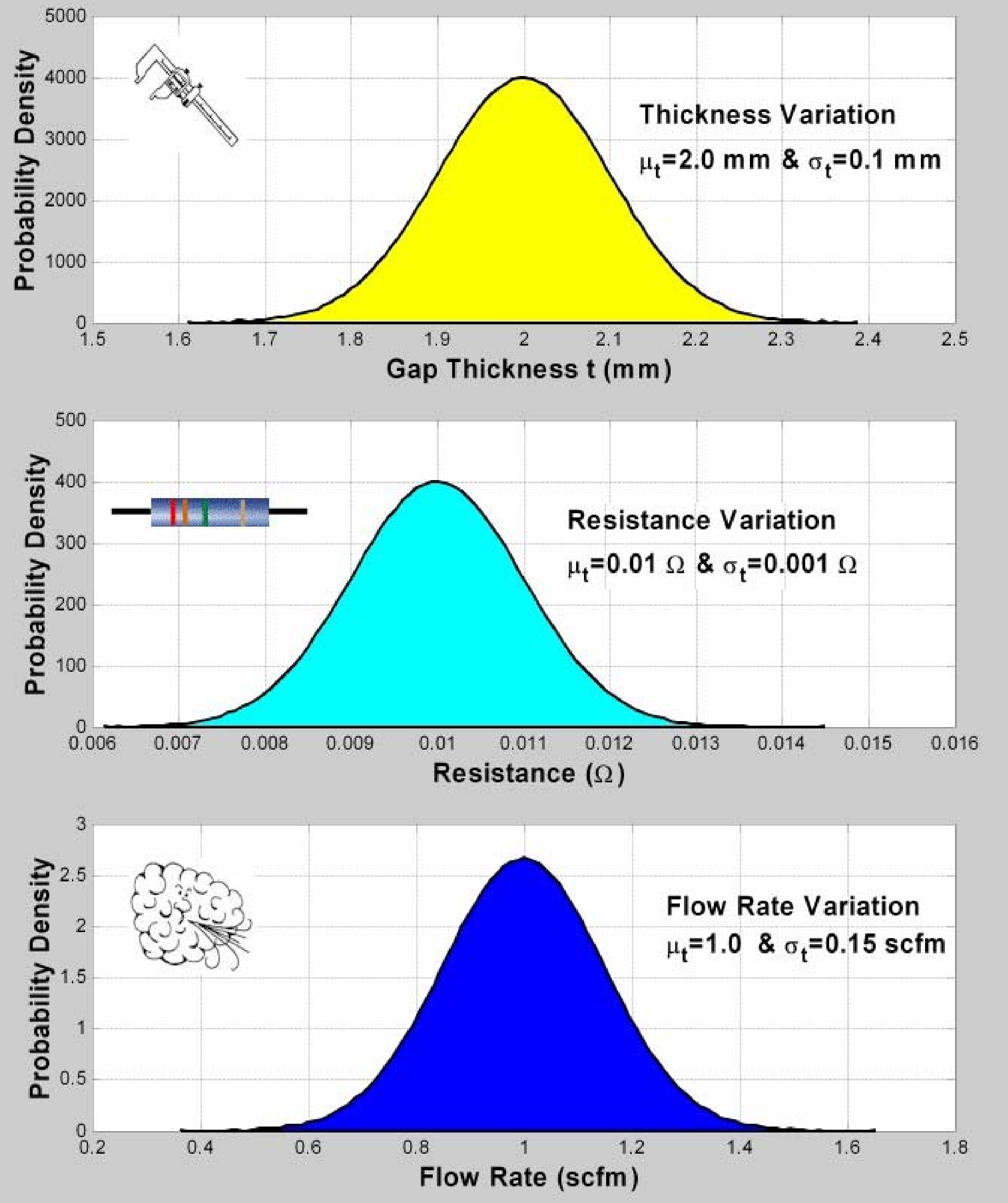
Inputs with Variation

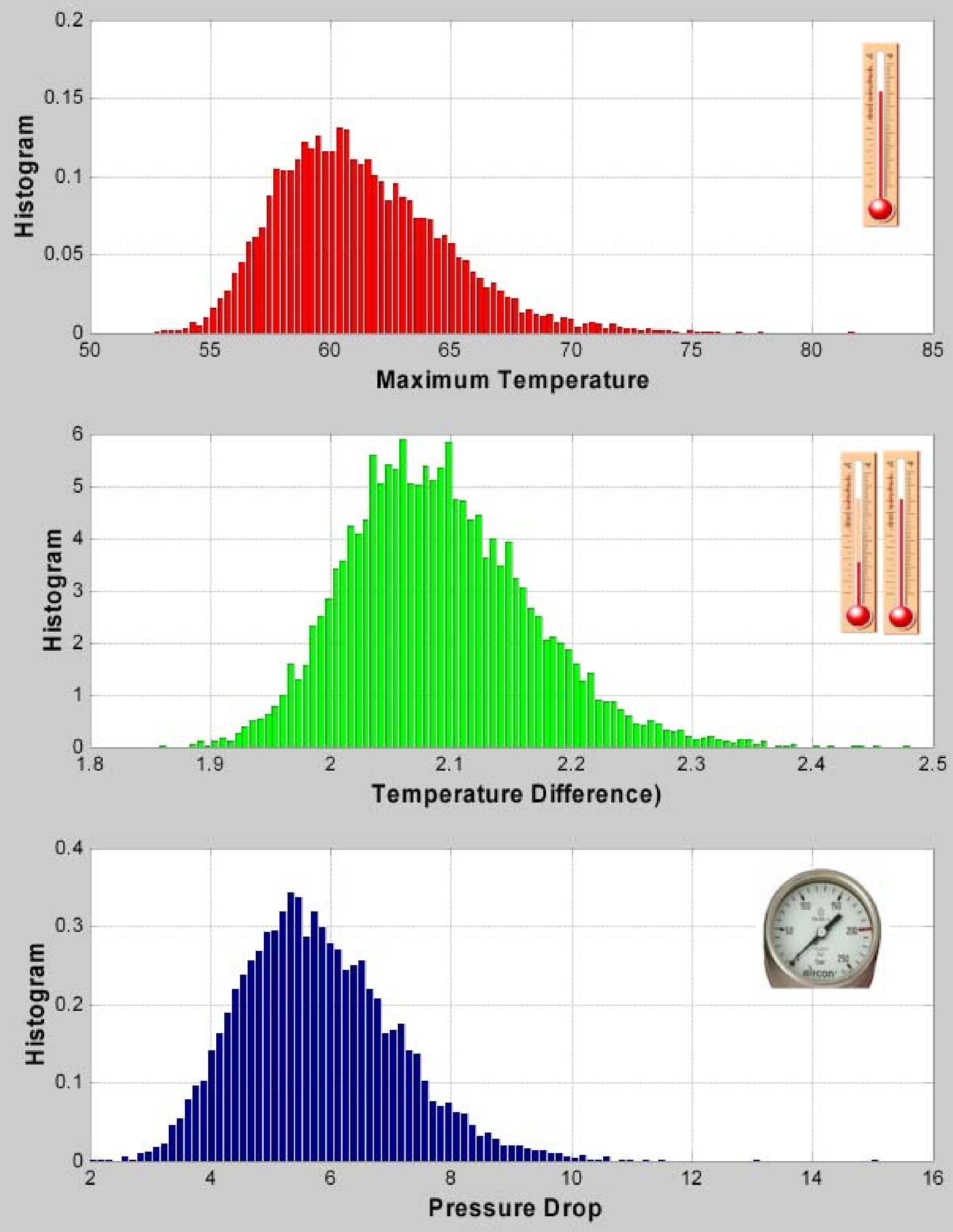
- Gap Thickness
- Cell Resistance
- Flow Rate
- Six input parameters:
  1. μ_{tgap}
  2. σ_{tgap}
  3. μ_R
  4. σ_R
  5. μ_{Frate}
  6. σ_{Frate}





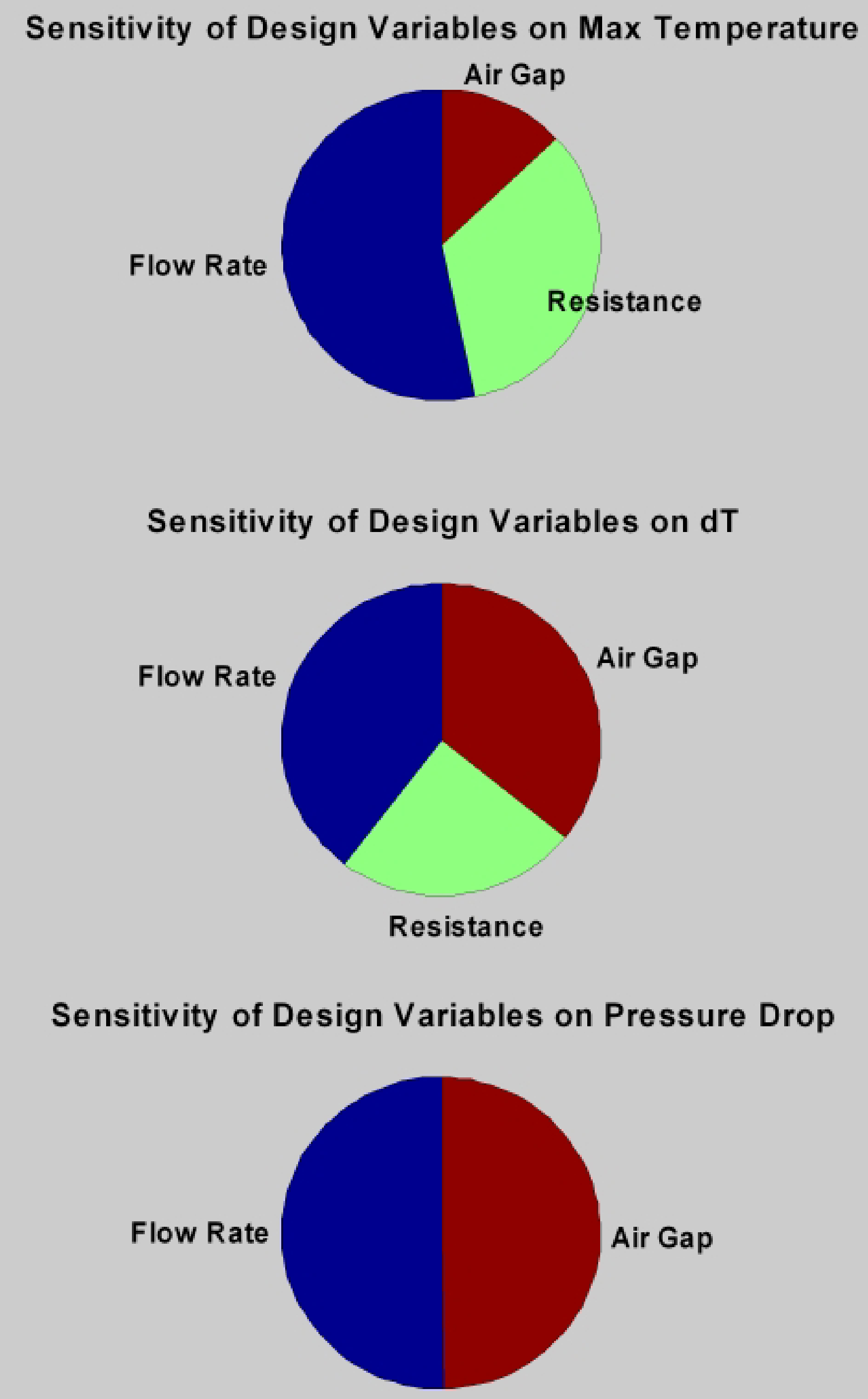
Outputs

- SMART Attributes
  - Simple
  - Measurable
  - Agree to
  - Reasonable
  - Time-based
- Outputs – variation
  - max temperature
  - differential temperature
  - pressure drop
- Six input parameters:
  - $\mu_{Tmax}, \mu_{dT}, \mu_{dP}$
  - $\sigma_{Tmax}, \sigma_{dT}, \sigma_{dP}$

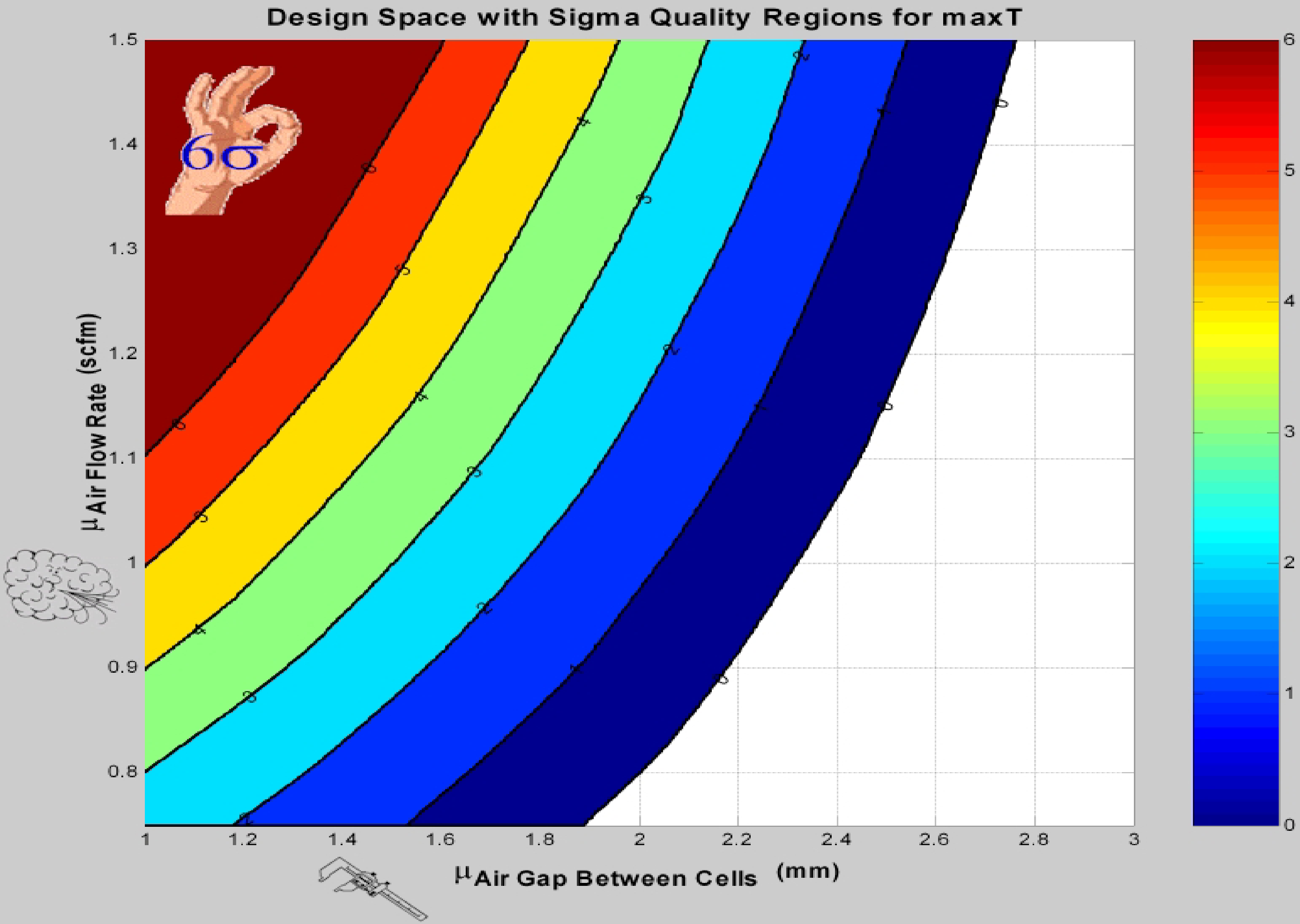


Sensitivity Analysis

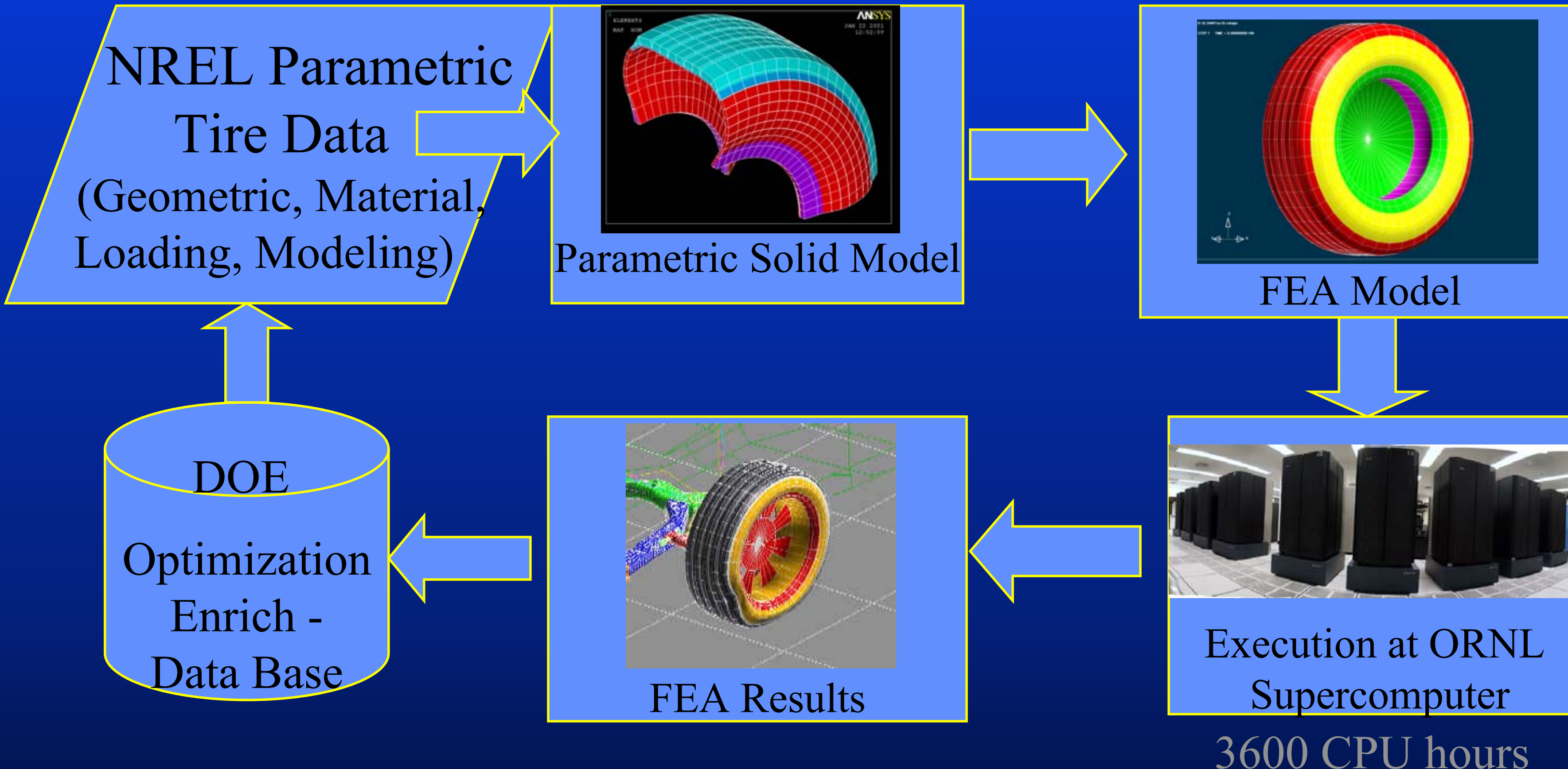
- Sensitivity of the design variables on the response attributes
  - The flow rate has the most impact on the maximum temperature
  - All three input design variables have about equal effect on the temperature differential
  - The internal battery resistance has no effect on the pressure drop.



Design Space with σ Quality Regions T_{max}

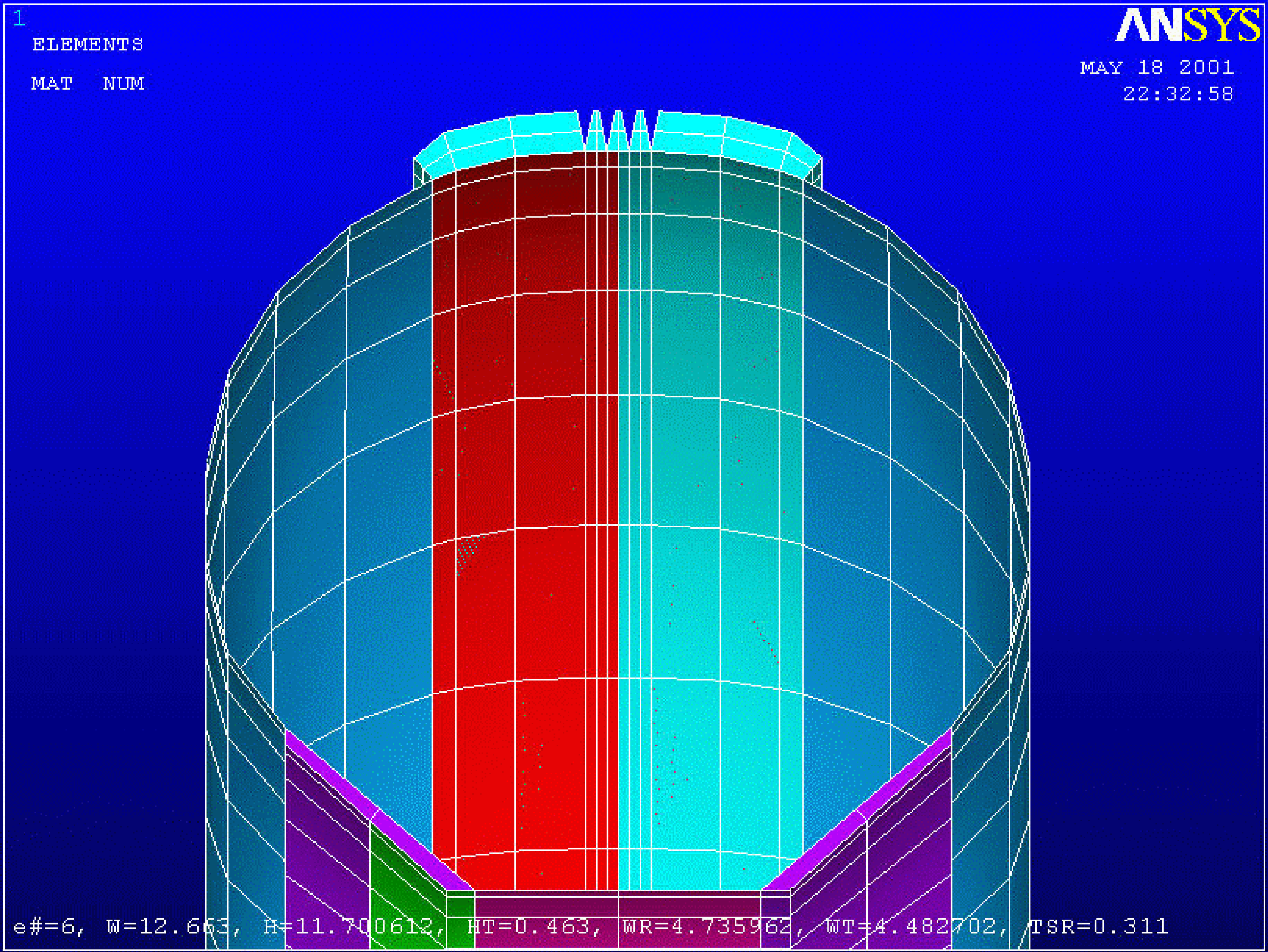


Design of Experiments Techniques for Road Load Reduction



- Improving the loads prediction capability using an accurate tire model would assist in minimizing vehicle weight while creating durable vehicle structure

Tire Geometry Morphing



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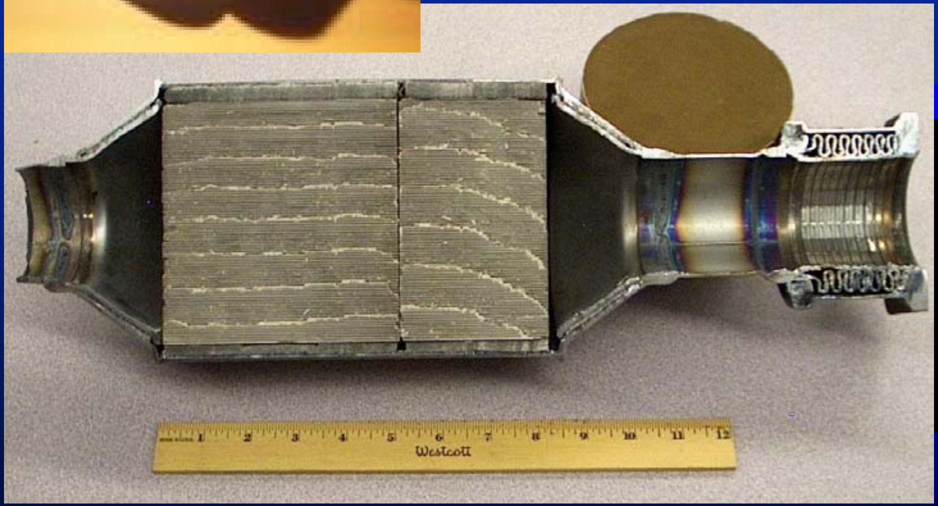
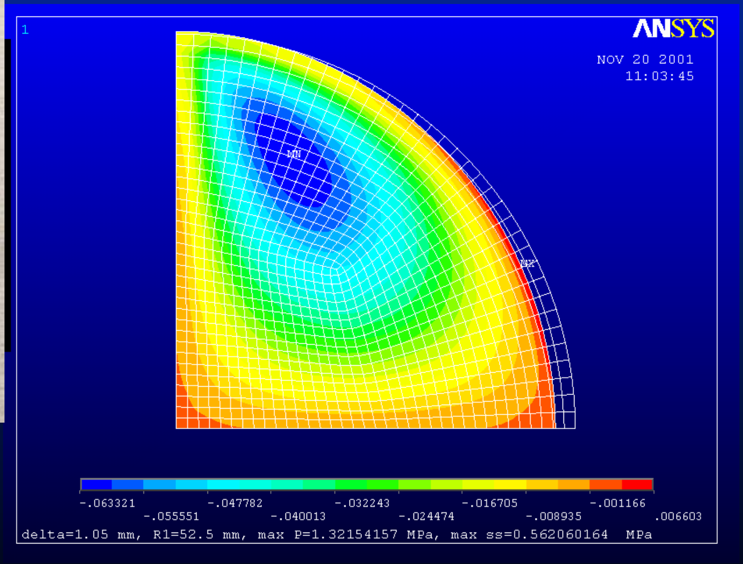
Catalytic Converter Section

Catalytic Converter Failure Avoidance Study

- If $\Delta = \Phi_{max} - \Phi_{min}$, $\tau_{allowable}$ exhibits a given variation identify the supplier specification (maximum standard deviation of Δ) in order to achieve six-sigma quality





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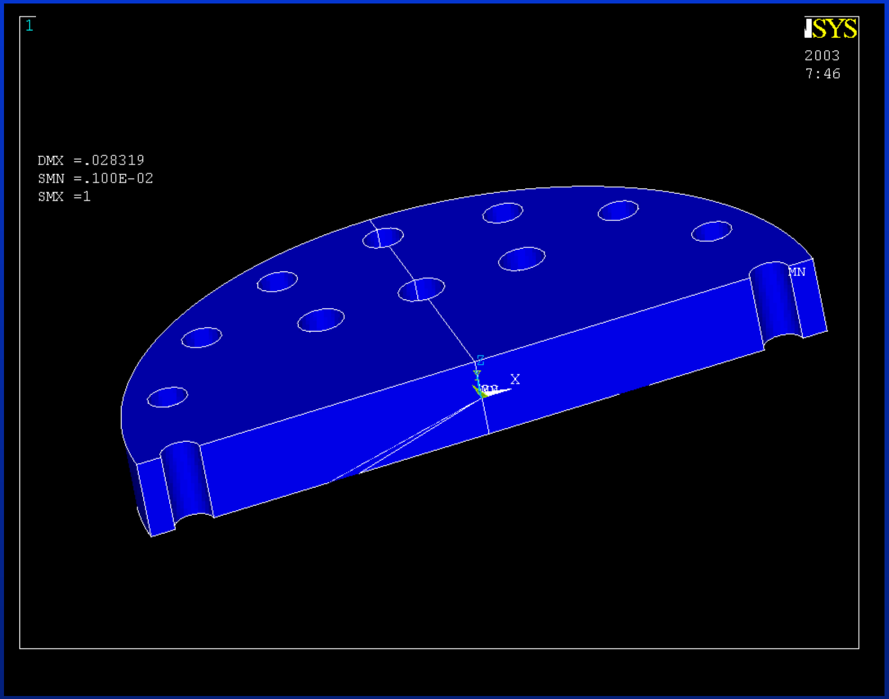
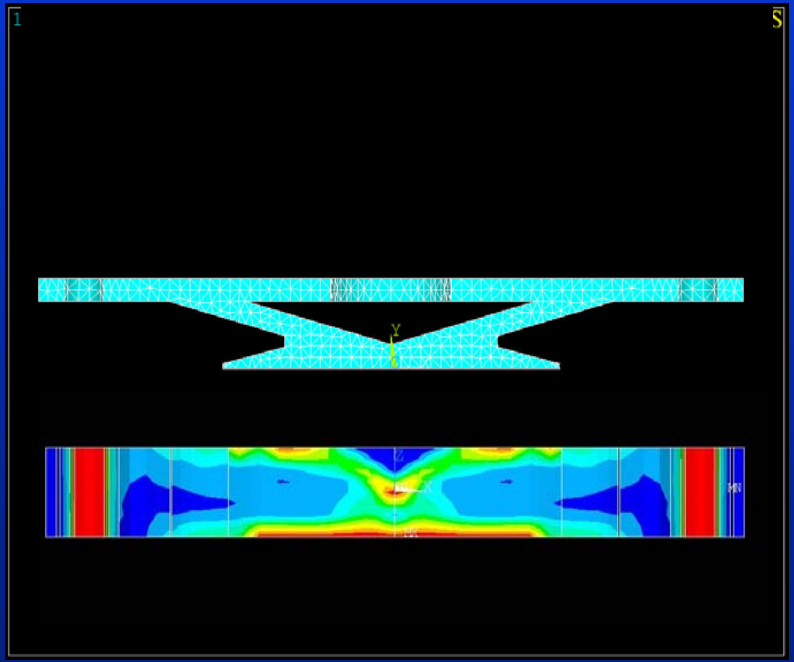
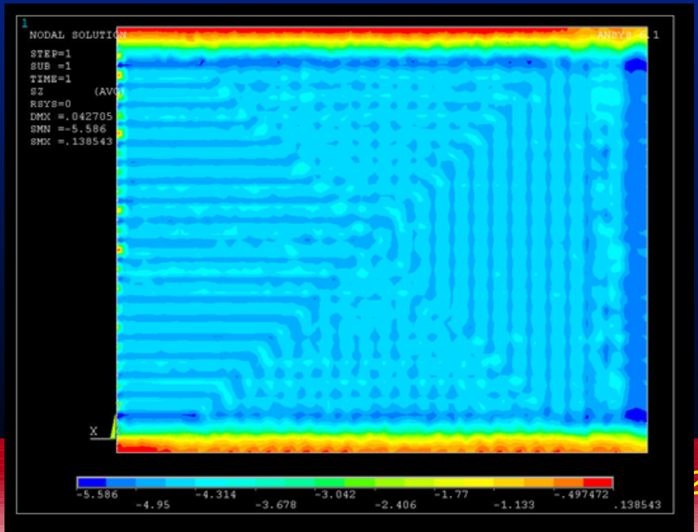
Topology Optimization of Fuel Cell Endplates





RIT Paper investigates "Effect of Material and Manufacturing Variations on MEA Pressure Distribution"



What's Next?

How can you use these techniques in your program ?